EVAPO-TRANSPIRATION: EXCERPTS FROM SELECTED REFERENCES

Compiled by

Howard W. Lull

VICKSBURG INFILTRATION PROJECT,
SOUTHERN FOREST EXPERIMENT STATION, U. S. FOREST SERVICE
In cooperation with
WATERWAYS EXPERIMENT STATION, CORPS OF ENGINEERS

OCCASIONAL PAPER 131 August 1953

Cover photo: An experimental site operated by the Vicksburg Infiltration Project. Soil moisture, solar radiation, and weather measurements are made at this site daily. The shelter on the left houses fiberglas soil-moisture unit terminals and recording potentiometers. In the center is an evaporation pan, anemometer, weather shelter and recording raingage. In the right background are total and net exchange radiometers and plots where soil-measure units are installed.

ACKNOWLEDGMENT

This publication was prepared in connection with the work of the Vicksburg Infiltration Project, Vicksburg, Mississippi. The Project is a cooperative effort of the Southern Forest Experiment Station, Forest Service, U. S. Department of Agriculture and the Waterways Experiment Station, Corps of Engineers, U. S. Army.

Mr. M. D. Hoover of the U. S. Forest Service and Dr. Earl L. Stone, Jr., of Cornell University reviewed the initial list of references and suggested several that were subsequently included. Mr. George B. Herring of the Vicksburg Infiltration Project was responsible for copying and proofreading the excerpts.

The compiler is grateful to the authors and publishers of the original references for permission to use copyrighted material.

CONTENTS

EVAPO-TRANSPIRATION: EXCERPTS FROM SELECTED REFERENCES

Compiled by Howard W. Lull
Southern Forest Experiment Station

Evapo-transpiration is the process by which water moves from the soil to the atmosphere. As the link in the hydrologic cycle influenced by vegetation, its importance matches its complexity. While recent research has provided a better understanding of the process, there is as yet no publication that summarizes the present state of knowledge in this field. The purpose of this compilation, which was originally intended only for use of the staff of the Vicksburg Infiltration Project, is to give the reader a birds-eye view of the subject as it is understood today. The best way of accomplishing this seemed to be to let some of the authorities speak for themselves.

The compilation may be useful in providing some source material, but by no means does it cover the entire subject. Those interested in reading further should consult the original references. Most of these will cite other works which bear study, ad infinitum, for there is a labyrinth of literature on the subject. Many studies will be found which deserve but are not given a place in this compilation. Space limitations and, unfortunately, oversight have prevented their inclusion.

The abundance of literature attests the complexity of evapo-transpiration. Largely, this complexity stems from the nature of the process: partly physical and partly physiological. Physically, evapo-transpiration involves the amount of energy received from the sun and the forces which hold water to the soil. The first varies principally with the time of day, season of the year, and latitude; the second, with the wetness and temperature of the soil, and the concentration of the soil solution. Physiologically, the plant is involved from root hair to uppermost stoma. To add to the complexity, evapo-transpiration can be studied in the laboratory or in the field, with portions of plants, entire plants, or plant communities--and with results that are sometimes as disparate as the methods.

With all these complexities, the effect of evapo-transpiration is relatively simple. Through the process the water stored on and in the soil is returned to the air. As the soil dries, water supplies for plant growth are decreased while storage space for the next rainfall is increased. Therein reside the practical implications of evapo-transpira-

tion for crop production, as a means of influencing the distribution of water supplies, and for flood control. Knowledge of evapo-transpiration rates is useful in scheduling delivery of irrigation water. The possibility of reducing transpiration by manipulation of vegetation, and thus increasing streamflow, has received recent attention. Conversely, the maintenance of heavy growths of vegetation which transpire maximum amounts of water and provide maximum amounts of storage space has application in flood control.

These lines of application give importance to results of recent research on evapo-transpiration. Much of this work has been fundamental, resulting in a better understanding of the process and opening new avenues of application. By contrast, much of the earlier work was based on empirical studies of water requirements and transpiration ratios.

From the more recent research, one conclusion stands out which is as important as it is simple: during the growing season, rates of evapo-transpiration are governed first by the availability of water supplies. When and where supplies are ample, rates are controlled by atmospheric factors, the nature of vegetation, or both acting together. Where supplies are limited, the rates of loss are principally a function of the amount of available soil moisture. To this must be added the observation that, country-wide, supplies are for the most part limiting.

These considerations render suspect determinations of evapo-transpiration from vegetation growing in soil kept at high moisture content. Major reliance must be placed on studies made under more natural conditions of limited moisture supplies. Involved, then, are the forces by which vegetation can remove water and the opposing forces which hold water in the soil. Root habits of vegetation assume pertinence, for it is by root growth that much of the soil moisture supply becomes accessible to the plant. Soil structure and depth and other factors affecting root growth also become important.

Contents

The excerpts that follow cover several different aspects of evapo-transpiration. To delineate these and to provide some order in the presentation of the references, six subject-matter headings are used. References which deal with one or more of these subjects are included under the subject principally concerned.

A brief review of the material under each heading follows:

General discussion.-- The first sources consulted during the preparation of these excerpts were textbooks and papers which summarize present knowledge. These sources cover in a general way some of the more specialized references under the other five headings. Included in this section is material on such subjects as the means by which plant roots secure water (1, 4, 5); 1/ the forces involved in the removal of water from the soil by vegetation (1, 2, 3, 4, 5, 6); the relation of root growth and distribution to water removal (4, 5, 7); the availability of water throughout the soil moisture range (3, 4, 5, 7); comparison of the evaporation and transpiration processes (3, 6); and the effect of soil moisture content (3, 6, 7), water table depth (1, 6), and climatic factors (1, 3, 7) on evapo-transpiration.

Evaporation.-- References concerning evaporation from bare soil deal principally with expositions of the process (10, 11, 14, 15); or the influence of various site factors upon it such as climate (8, 9, 10, 11, 12, soil temperature (13, 20), water table depth (11, 16), and, of considerable importance, soil-moisture content (8, 12, 20). Some consideration is given to evaporation under summer and winter conditions (9, 10, 11); to the moisture-conserving effect of dry surface soil (10, 11 19); to soil compaction (12) and puddling (15); and to the effect of rainfall on water table losses (17, 18). The last reference in this section (21) summarizes existing knowledge of evaporation from forest soils.

Transpiration.-- This section begins with an interesting reference (22) on the probable origin and essential wastefulness of the transpiration process. Certain physiological aspects are discussed in references 23, 26, 28, 29, 32, and 33. The effects of such weather factors as air temperature, humidity, wind, and light intensity are considered in several of the references (23, 24, 25, 26, 27, 28). Soil temperature is also discussed (25, 30). Transpiration during the winter is described (29, 30).

The influence of soil moisture on transpiration rate is noted in reference 31, dated 1905, and in several more recent works (25, 27, 31, 32, 33, 34, 35, 36). The distinction as to whether atmospheric factors or soil moisture supply govern transpiration rate is clearly brought out (34, 36), as well as the error in the concept of "transpiration ratio" (35).

1/ Numerals refer to numbers preceding reference titles.

<u>Evapo-transpiration.</u> -- A number of these references (37, 38, 45, 46, 47, 48, 49) deal with use of the energy balance or solar radiation data in some form as a means of understanding the evapo-transpiration process or estimating its rates. All of these apply to situations where water supplies are not limiting. Three different methods of estimating evapo-transpiration rates or seasonal losses are given (38, 45, 49). Where water supplies are limited, water losses and factors affecting them are given for several different types of vegetation (39, 40, 41, 42, 43), together with methods for estimating soil moisture content for such areas (44, 67). How the removal of vegetation affects water losses is described for three areas (42, 43, 64). Three references (46, 47, 48) deal with the concept of potential evapo-transpiration, and one example (49) illustrates the use of this concept.

<u>Roots and soil moisture.</u> -- Since roots are the means by which vegetation removes water from the soil, their growth and distribution are of particular import to an understanding of evapo-transpiration. Factors which affect the entry of water into a root are noted (50, 55). The extent of the root system and the relation of its distribution at various depths to rates of water removal are described (51, 52, 53, 54, 55, 56). Other references show that root growth is important in making water available to the plant (57), but that growth may or may not be inhibited by dry soil (58, 61). Under certain conditions suberized roots play an important part in water absorption (59). When the soil is dry, water vapor may furnish a source of supply (60), or water may move from the plant to the soil (61). The effect of rooting habit on the capacity of vegetation to remove water from the soil is described (62, 63, 64, 65, 66, 67).

<u>Roots.</u> -- An understanding of the important role that roots play in evapo-transpiration gives a new significance to literature on root growth and habits, permitting inferences as to their probable effect on evapo-transpiration. For instance, the effects on evapo-transpiration of soil factors affecting root growth (68, 69), of seasonal root growth (70, 71, 72), and of stages of root growth in a forest plantation (73) can be easily inferred. Likewise the differences in root habits of crops grown in different climates (74), and the effects of subsoil development (75) and of different intensities of grazing (76) can be estimated.

GENERAL DISCUSSION

1. THE NATURE AND PROPERTIES OF SOILS

T. L. Lyon, H. O. Buckman, and N. C. Brady. 591 pp. Macmillan, New York. 1952. (Reprinted by permission.)

[Pp. 210-213] "At any one time only a small proportion of the soil water lies in the immediate neighborhood of the adsorptive surfaces of plant root systems. Consequently, a query arises as to how the immense amount of water necessary to offset transpiration is so readily and steadily acquired by vigorously growing crops. Two phenomena seem to make adequate and continuous contact possible if the soil is in good condition for the plant growth: (1) the capillary adjustment of the soil water and (2) the extension of the root system of plants, especially when the elongation is rapid.

"Rate of capillary movement. When plant rootlets begin to absorb water at any particular point or locality in a moist soil, the thick water films at the capillary fronts are thinned and their curvatures increased. This intensifies the capillary pull in this direction and water tends to move toward the points of plant absorption. The rate of movement depends on the magnitude of the tension gradients developed and the conductivity of the soil interstices.

"With some soils the above adjustment may be comparatively rapid and the flow appreciable; in others, especially heavy and poorly granulated clays, the movement will be sluggish and the amount of water delivered meager. Thus, a root hair, by absorbing some of the moisture with which it is in contact, automatically creates a tension gradient and a flow of water is initiated toward its active interfaces.

"How effective the above flow may be under field conditions is questionable. Many of the early investigators greatly overestimated the distances through which capillarity may be effective in satisfactorily supplying plants with moisture. They did not realize that the rate of water supply is the essential factor and that capillary delivery over appreciable distances is very slow. Plants must have large amounts of water regularly and rapidly delivered. Therefore, capillarity, although it may act through a distance of a foot or two, if time be given, may actually be of importance through only a few centimeters as far as the hour by hour needs of plants are concerned.

"The above statement must not be taken to mean that the slower and long-ranged capillary adjustments are in the aggregate not important. They are important but in a broader and more seasonal way. Nor are

gravitational and vapor transfers to be ignored entirely even in this hour-by-hour watering of plants.

"Rate of root extension. This limited water supplying capacity of capillarity directs our attention even more forcibly to the rate of root extension and here early workers made an underestimate. They failed to recognize the rapidity with which root systems expand and the extent to which new contacts are constantly established. During favorable growing periods, roots often elongate so rapidly that satisfactory moisture contacts are maintained even with a lessening water supply and without any great aid from capillarity. The mat of roots, rootlets, and root hairs in a meadow, between corn or potato rows, or under oats or wheat is ample evidence of the minutiae of the ramifications.

"The rate of root extension is surprising even to those engaged in plant production. On the basis of the data available the elongation may be rapid enough to take care of practically all of the water needs of a plant growing in a soil at optimum moisture. If this be the case, the plant is more or less independent of capillary adjustment for its immediate water supply.

"As long as the force with which soil water is held is comparatively low, that is, in the tension range centering around .5 of an atmosphere, a vigorously growing plant should have little difficulty in obtaining water rapidly enough to offset transpiration. Its roots are ever pushing into moisture loosely held and absorption should be easy. In addition, capillary conductivity should bring in some low-energy water from neighboring zones.

"But, if the root zone receives no new supply of water, a different condition soon develops. As the moisture of the soil is gradually reduced by surface evaporation and plant absorption, the water remaining is held with ever-increasing tenacity. Absorption by the plant becomes more and more difficult against the higher and higher tensions. At first the plant is able to adjust to the diminished intake. Soon, however, the tension is such that the absorption by the plant will barely meet its transpiration losses. Obviously if water is not applied at this critical stage the plant will wilt, at first temporarily, then permanently. And the phenomenon occurs not because the plant is absorbing no water but because the intake, due to the high negative tension of the soil moisture, is too slow to offset transpiration. The percentage of moisture within the zone of influence of the plant roots when permanent wilting first occurs is called the wilting coefficient or the critical moisture point."

The transpiration ratio (i.e., pounds of water transpired per pound of above-ground dry matter produced) ranges from 200 to 500 for crops in humid regions, and almost twice as much in arid climates.

[P. 222.] "Much of the variation observed in the [transpiration] ratios quoted arises from differences in climatic conditions. As a rule, the less the rainfall, the lower is the humidity and the greater is the relative transpiration. This accounts for the high figures obtained in arid and semi-arid regions. In general, temperature, sunshine, and wind vary together in their effect on transpiration. That is, the more intense the sunshine the higher is the temperature, the lower is the humidity, and the greater is likely to be the wind velocity. All this would tend to raise the transpiration ratio.

"The factors inherent in the soil itself are of special interest as regards transpiration, since they can be controlled to a certain extent under field conditions. In general, an increase in the moisture content of a soil above optimum results in an increased transpiration ratio. This has been established by a number of investigators.

"Moreover, the amount of available nutrients and their balanced condition are also concerned in the economic utilization of water. The data available show that the more productive the soil, the lower is the transpiration ratio provided the water supply is held at optimum."

Concerning factors affecting evaporation at the soil surface (pp. 225-226):

"Relative humidity. Any changes in the vapor-pressure gradient and hence in the rate of evaporation will be determined by fluctuations in the relative humidity of the atmosphere immediately above. The lower the relative humidity the more pronounced will be the vaporization tendency. Sometimes the relative humidity of the atmosphere approaches 100 per cent. Under this condition evaporation might not only cease but condensation could be induced. Since relative humidity fluctuates rather widely from time to time, it cannot but exert a variable yet important influence upon the loss of water from soil by evaporation."

"Temperature. In direct sunlight the soil and its water often have temperatures several degrees above that of the atmospheric air. This increases the vapor pressure and so markedly steepens the gradient that evaporation is greatly encouraged."

"In fact this temperature effect on vaporization is usually much more important than that resulting from a lowering of the relative

humidity of the air. For instance, raising the temperature of the water only 5 $^{\circ}$ C. above that of the atmospheric air is equivalent in its effect on the vapor-pressure gradient to a lowering of the relative humidity about 35 per cent. Hence, temperature difference is a major control of the vapor-pressure gradient and, therefore, of the surface evaporation of water from soils.

"Wind. At the same time, if a dry wind is stirring, the accumulated water vapor is continually swept away, the moist air being replaced by that with a lower relative humidity. This tends to maintain the vapor-pressure gradient and evaporation is greatly encouraged. The drying effect of even a gentle wind is noticeable even though the air in motion may not be at a particularly low relative humidity. Hence, the capacity of a heavy wind operating under a steep vapor-pressure gradient to enhance evaporation both from soil and plants is tremendous. Farmers of the Great Plains dread the hot winds characteristic of that region."

"In respect to the depth to which soils may be depleted by this evapo-capillary pumping, soil physicists are agreed that the distance is far short of the 4, 5, or even more feet sometimes postulated. The conditions that impede and interrupt the flow are such as to allow it to deliver important amounts of water to the surface only through comparatively short distances. Some investigators think that the rate of evaporation is often so rapid as to cause the moisture column to break relatively near the surface, and that this is one of the major inhibitions. But whatever the explanation, a 20- or 24-inch depth is probably a maximum range."

2. SOIL CONDITIONS AND PLANT GROWTH

Sir E. John Russell (Recast and rewritten by E. Walter Russell).
635 pp. Longmans, Green and Co., London. 1950.
(Reprinted by permission.)

[Pp. 370-371.] "One consequence of the amount of water used by crops depending primarily on the energy supply or the evaporation power of the air, is that all the water falling on the crop, whether as light drizzle or dew or whether as a definite rain storm, is as effective in contributing to the water requirements of the crop as is the water removed from the soil...every thousandth of an inch of rainfall, however long it takes to fall, on being evaporated from the plant leaves or stems reduces the plants' demands on the soil water by this amount."

[Pp. 372-3.] "Plant roots can only extract water from a soil if they can apply a sufficiently great suction to move it out of the pore space. As the soil dries, so the suction needed to extract water rises and the rate of movement of water into a given length of root decreases, which may sometimes have the consequence that if the crop is growing in conditions conducive to high rates of transpiration, the actual maximum rate it can reach will decrease as the soil dries. The maximum suction roots can exert on the soil water does not appear to be a very definite quantity, but if the water is held at suctions higher than about 7 atm.--the first permanent wilting point of the soil--the roots appear to be unable to extract sufficient water to keep the whole plant of most farm crops turgid when placed in a saturated atmosphere, i.e., in an atmosphere when transpiration cannot take place; and if above about 20 to 30 atm.--the ultimate wilting point--to keep any leaves turgid. The water held between these two suctions is sufficiently available to the roots for the maintenance of life, but not for growth; that held at suction less than that corresponding to the first permanent wilting point may be, but is not necessarily, readily available for growth."

[P. 374.] "The soil water is only at a suction of between 10 to 15 atm. or over in a soil carrying a permanently wilted crop if the osmotic pressure of the soil solution is low. If it is appreciable, the plants wilt permanently when the soil water is at lower suctions than this. The ease with which plant roots extract water from the soil seems to depend, not on the suction of the water in the soil, but on its free energy; and these two are only equivalent when the water contains no dissolved substances. The free energy of a solution in a soil is approximately the sum of the free energy changes due to the dissolved salts and that due to the curved air-water menisci bounding the solution in the soil pores...Hence if the osmotic pressure of the solution is 3 atm. and it is under a suction of 3 atm. in the soil pores, then plant roots will have at least the same difficulty in using the water from this solution as they would if the soil contained pure water at a suction of 6 atm."

3. PLANT AND SOIL WATER RELATIONSHIPS

Paul J. Kramer. 347 p p. McGraw-Hill, New York. 1949.
(Reprinted by permission.)

[P.44.] "...Water flows under the influence of gravity, moves in capillary films, and diffuses as vapor, [always moving] along a gradient from regions of higher to regions of lower free energy."

[P. 57.] "It is generally agreed that transpirational losses exceed losses by evaporation where well-developed grasslands and forests occur. If evaporation removes water only from the surface foot of soil, the remainder of the soil moisture would remain untouched were it not for the roots of plants."

[P. 59.] "In general, it appears that, on an acre basis, considerably more water is lost by transpiration if the supply is always abundant than if it is somewhat limited at times. This is partly because larger shoots are produced when there is an abundance of water and partly because the rate of transpiration in this case is less often retarded by wilting and stomatal closure."

[Pp. 65-66.] "From the standpoint of energy involved in movement of water from soil to plant, there can be little doubt that soil moisture becomes less and less readily available as the moisture content decreases from field capacity to the permanent-wilting percentage. As the moisture content of the soil decreases, there is inevitably an increase in the amount of energy required to move a unit mass of water a unit distance. In another sense, however, at least in light soils, soil moisture may be practically as readily available to the plant at moisture contents just above the wilting percentage as at the field capacity; that is, in the sense that under some conditions water may be absorbed and transpired at the same rate in drier soils as in soils at the field capacity. This is because, as the moisture content of the soil and the moisture content of the plant decrease, the osmotic pressure and the diffusion-pressure deficit within the plant increase. While an increase of a few atmospheres in the diffusion-pressure deficit of the roots may supply the increased energy gradient necessary to maintain a high level of absorption, it does not appreciably reduce transpiration. In a sandy soil thoroughly permeated with roots, plants might reduce almost the entire soil mass nearly to the wilting percentage before transpiration decreases or the plants exhibit symptoms of a deficit. In heavy soils where root distribution is variable and sparse, as in the lemon orchards of southern California and the pear orchards at Medford, Oregon, the water is not uniformly absorbed from the entire soil mass and one cannot say that there is a definite moisture content above which water is available and below which it is unavailable."

[P. 67.] "For practical purposes, however, in many sandy soils water may be regarded as being equally available over most of the range from field capacity to permanent wilting. This is because the moisture-tension curve of most soils is hyperbolic and most of the range of readily available water lies in the flat portion of the curve. Most of the readily

available water is removed from light soils before the tension on the remainder exceeds 1 atmosphere, and only a small fraction is held with sufficient force to hinder absorption. This is not true, however, in heavy clay, where 50 per cent or more of the available water sometimes is held with tensions in excess of 1 atmosphere. In such soils water actually does become limiting to growth before the moisture content is reduced to the permanent-wilting percentage."

[P. 94.] "Since the field capacity is the amount of water held against gravity by a soil, it is obviously impossible to wet any soil mass to a moisture content less than its field capacity."

[P. 211.] "It seems certain...that when transpiration is rapid the active absorption mechanism responsible for root pressure is not only inadequate to supply the required amount of water but actually becomes inoperative, because of the increasing diffusion-pressure deficit in the root cells. Under these conditions, the intake of water is not a special function of the root cells but is a function of the entire plant, the root cells merely providing an absorbing surface, through which water is absorbed. To put it another way, in freely transpiring plants water is absorbed through the roots, rather than by the roots."

[P. 233.] "It is concluded that the principal cause of reduced intake of water by transpiring plants in cold soil is the physical effect of increased resistance to water movement across the living cells of the roots. This results from the combined effects of the decreased permeability and increased viscosity of the protoplasm of the living cells in the roots and the increased viscosity and decreased diffusion pressure of the water intake. Other factors, such as decreased root extension, water-supplying power of the soil, and metabolic activity of the roots, are of distinctly secondary importance."

4. SOIL MOISTURE IN RELATION TO PLANT GROWTH

F. J. Veihmeyer and A. H. Hendrickson.
Annual review of plant physiology 1:285-304. Annual Reviews, Inc., Stanford, Cal. 1950. (Reprinted by permission.)

"The upper and lower limits of water storage in the soil reservoir are fixed by two soil-moisture conditions, which might be called soil-moisture constants. In fact, the authors believe they are the only ones of any practical value for consideration in connection with plant growth. The first of these, the field capacity, is the amount of water

held in a soil after excess water has drained away and the rate of downward movement has materially decreased. This usually takes place within two or three days after rain or irrigation in pervious soils of uniform structure and texture. Below the first foot and in the absence of vegetation the field capacity persists for months without much change."

"The lower limit of the soil reservoir or the moisture content at which we may consider it to be emptied, since it no longer contains sufficient water to maintain normal growth and vigor of plants, is the permanent wilting percentage."

"Briggs and Shantz' conclusion that all plants wilt at the same moisture content when grown on the same soil has been questioned by a number of investigators...The authors have tested many plants by growing them in the same kind of soils in small containers and also in field trials. The results substantiate the conclusion of Briggs and Shantz, which now seems to be accepted by most investigators."

"...The moisture-extraction curves from field samples show only a slight reduction after the permanent wilting percentage is reached. This reduction is small, often not more than 1 per cent, even after three or four months. These extraction curves practically coincide year after year, both as to slope and as to minimum moisture content reached."

"The authors [1945] believe that the wilting range is much narrower for plants in the field than for those in containers. They define the permanent wilting percentage not as a unique value but as a small range of soil-moisture contents within which permanent wilting takes place. This range need not exceed 1 per cent for fine textured soils or 0.5 per cent for coarse textured ones."

"Typical vapor pressure curves for soils show the small decrease in vapor pressure from the field capacity to the permanent wilting percentage and the very rapid decrease thereafter. The position of the permanent wilting percentages on these curves near the region where the tightness with which the water is held by the soil increases very rapidly is significant."

The authors review literature on the relation of transpiration, photosynthesis, and plant growth to soil moisture content. They point out conflicting evidence and make a strong case that these processes are not affected as long as the moisture content is above the permanent wilting percentage.

"Physical measurements show that the energy required to remove water from the soil changes materially as the moisture content decreases, but it does not follow that the availability of the water to plants also decreases. By far the greatest drop in energy in the soil-moisture plant system occurs at the surface of the leaf cell walls which surround the sub-stomatal surface as Gradmann [1928] and Edlefsen [1942] have pointed out. The latter, from Thut's [1939] data, has calculated the drop in free energy between the leaf tissues and the outside air 1/ of -9.231×10^8 ergs per gm. The total free energy of the water surrounding the roots at the permanent wilting percentage may be taken to be about -0.16×10^8 ergs per gm. At 40 percent relative humidity, that of the air is -9.4×10^8 ergs per gm. or an overall drop of -9.24×10^8 ergs per gm. from the soil to the air. The increase in energy required when the soil moisture is reduced from the field capacity to the permanent wilting percentage is unimportant when the system as a whole is considered."

"The reason that plants wilt may be explained by the position of the permanent wilting percentage on the energy soil moisture curve in the region where a slight decrease in moisture content results in a great increase in resistance to removal of the water. Failure of the water supply to the plant, of course, may be due to the slowness of movement of water into the mass of soil dried by the roots."

"Another cause of water deficiency at soil-moisture contents near the permanent wilting percentage may be the failure of roots to elongate rapidly enough into regions where there is still water above the permanent wilting percentage."

"Whether water is readily available to plants or not in the final analysis must be decided by empirical experiments. While the results of growing plants in containers may indicate trends, they should not be taken as being conclusive unless confirmed by field trials."

"One difficulty with plants in the field is the sparse root-development of some plants. Sometimes, either due to soil conditions or inherent characteristics of the plants, roots will not thoroughly permeate the soil. Consequently, neither soil sampling nor measurements of soil properties which are related to soil-moisture contents, made with physical instruments inserted into the soil, will give reliable records of the actual moisture content of the soil in contact with the absorbing portion of the roots. Thus, erroneous conclusions may be drawn."

1/ From correspondence with F. J. Veihmeyer: "In references to the total free energy required at 40% relative humidity and 30 °C, that of the air is -12.8×10^8 ergs per gram in place of -9.4×10^8. This will give an over-all drop of -12.6×10^8 ergs per gram."

"Much of the material not reviewed does not contain sufficient data to permit an analysis because they were based on techniques which obviously are faulty. For instance, those in which it is purported to maintain a predetermined moisture in the soil in which plants are growing were not given consideration."

"The results of investigations on the relation of plant growth to soil moisture show that the plants grow well throughout a wide range of soil moisture, but some investigators question whether they do so with equal facility throughout the entire range from field capacity to permanent wilting percentage. The permanent wilting percentage is the most important soil moisture constant. The accuracy of its determination is highly important."

5. SOIL WATER AND PLANT GROWTH

L. A. Richards and C. H. Wadleigh. Soil physical conditions and plant growth, pp. 73-251. Academic Press, Inc., New York. 1952. (Reprinted by permission.)

[Pp. 82-83.] "On the basis of experiments by Lewis [1937], it is inferred that in the plant-growth moisture range and in the absence of temperature gradients, the movement of water in soils takes place primarily in the liquid phase through the pore channels or in the adsorbed film phase over the surface of the soil particles, and that compared with these processes, the movement of water in the vapor phase is negligible. This is reasonable, for the whole plant-growth moisture range corresponds to a relative humidity range of less than 2 percent, and therefore vapor-pressure gradients would always be small under isothermal conditions.

"If there is an appreciable temperature gradient, however, vapor transfer of water through field soils may be more important than film flow, particularly at moisture contents near the wilting percentage. However, little quantitative data on this point appear to be available. Field measurements in central California by Edlefsen and Bodman [1941] indicate that an upward movement of water takes place during the winter, apparently in response to the temperature gradient. Their measurements did not distinguish between vapor and film transfer, but it seems likely that vapor transfer was significant. Hilgeman [1948] measured the moisture content of a bare soil in Arizona to a depth of 8 feet during a period of 22 months. The total loss of water was 9.8 inches, or

47 percent of the water available for plant growth. The most rapid losses occurred in summer. In this case, also, it appears likely that vapor transfer under the action of temperature gradients played an important part in moisture loss from the subsurface soil."

[P. 84.] "The high tension in the soil moisture in the vicinity of the root sets up a tension gradient and thereby a force action in the soil-water system that tends to move water toward the root. This tendency of water to move toward plant roots in response to tension gradients is of considerable importance for perennial plants with large developed root systems because a small distance of movement over a considerable combined length of root system would account for an appreciable volume of water, even at the slow rates at which water moves through dry soil. However, for young plants with a newly developing root system this movement is so slow that sufficient water for normal growth would not be supplied unless the plant roots are able to extend themselves outward into a fresh soil-moisture supply. Therefore, as has been described by Davis [1940], when a new corn plant is developing, the available moisture is extracted in the vicinity of the base of the plant and the soil approaches the wilting percentage, whereas just a few inches farther away from the plant the soil may be at or near field capacity. The roots of the newly developing plant must extend themselves outward in order to maintain a continuous supply of available water. When the roots of the plant have permeated the soil region in which they can grow well, the soil-moisture content throughout the soil region occupied by roots will be reduced into the wilting range. Unless additional moisture is supplied by rain or irrigation, vegetative growth will cease and the plant will wilt."

[P. 85.] "In irrigated areas the pattern of moisture extraction for mature perennial tree crops has been extensively studied by Hendrickson and Veihmeyer [1929, 1934, 1942]. Starting with a deep permeable soil when the whole profile was wet, they found that moisture is continuously extracted at all depths down to 6 or 8 feet or deeper, depending on the soil and the species of tree. The surface 2 or 3 feet may approach the permanent wilting percentage at about the same rate. Often, however, the rate of extraction is greater near the tree and near the soil surface, so that available water is first depleted from the surface layers of soil.

"Veihmeyer and Hendrickson [1938] have used the pattern of moisture extraction as an indication of the probable root distribution, and state: 'The fact that soil samples taken at any place within the experimental plots in mature peach, prune, and walnut orchards which

have had an even application of water, agree at comparable depths, shows that these trees, under conditions existing at Davis, have a uniform distribution of roots.'

"Such observers assume that moisture depletion from a soil region is evidence that active roots traverse that region of soil. The effective distance through which water in the available range can move toward the root is certainly of the order of inches and not feet. The pattern of moisture extraction in soils is therefore largely a matter of the active root distribution. Root distribution, as recently discussed by Kramer [1949] is mainly determined by the genetic character of the plant but is modified by plant spacing as well as by soil and climatic factors."

[P. 103.] "Measurements and observations by Veihmeyer and Hendrickson [1927, 1938]; Aldrich, Work, and Lewis [1935]; and others have shown reasonably conclusively that moisture will not move from root-free soil at a moisture content below field capacity at a rate adequate to supply roots in adjacent soil at distances of the order of a number of centimeters away. Nevertheless, the fact that a wet sample of soil 1 centimeter deep can be brought in 24 hours to equilibrium with a membrane supporting a pressure difference of 15 atmospheres indicates that unsaturated permeability is not negligible in the moisture range above the wilting percentage. This fact further indicates that in a root zone where the maximum distance of soil from roots is less than 1 centimeter, soil-moisture tension gradients may largely disappear during the overnight period when transpiration is lessened."

[Pp. 108-9.] "The specific characteristics of the experimental plant must be taken into account in considering its response to soil-moisture conditions. The nature of the root system is especially pertinent. Kramer [1949] has given well-merited emphasis to the characteristics of root systems in his recent text on water relationships in plants. The extensive studies of Weaver [1926] and Weaver and Brunner [1927] show that the roots of various crop plants differ widely in their inherent capacity to penetrate deeply into the soil. Asparagus and alfalfa roots grow to depths of 12 to 15 feet or more, if the nature of the soil is favorable. Under such crops, soil-moisture studies confined to the surface foot or even the surface 3 feet might well be meaningless. On the other hand, soil-moisture investigations under such shallow-rooted crops as onions and potatoes would need to be largely concerned with the surface 2 feet of soil, for few roots of these crops extend beyond this depth. Differences among varieties of a given species may actually be involved in this consideration. Kiesselbach and Weihing [1935]

noted that upon hybridization, the depth of penetration and combined length of all main roots of corn increased materially in the first generation. This observation is probably related to the superior yields obtained with hybrid corn.

"In addition to the extent of root penetration, consideration must also be given to root proliferation or the special density of root distribution. Owing to the slow rate of unsaturated flow in soils, the exhaustion of soil moisture by plants is very dependent on thorough permeation of the soil mass by fine rootlets. Onions and celery characteristically have root systems exhibiting poor proliferation and permeation. Successful celery culture is largely dependent upon supplemental irrigation, even in humid climates. On the other hand, many of the grasses thoroughly permeate the soil with their fine roots. In consequence grasses not only efficiently remove available moisture from the fine interstices of the soil but also are especially effective in generating good structural characteristics in the soil. It appears that these two effects are to some extent related."

[Pp. 144-5] "From the irrigation and soil-moisture experiments mentioned in the foregoing sections it is apparent that there is considerable evidence that significant differences in growth rates occur along with varying degrees of moisture depletion within the so-called available soil-moisture range. In the interpretation of the statement that soil moisture is equally available until moisture is depleted about to the wilting percentage, several factors should be kept in mind. Both from the standpoint of supporting evidence and applications, use of the term 'available' in this connection should be restricted in its meaning to the rates of soil-moisture extraction and water use by plants. Various experimenters have found that during an irrigation cycle the rate at which an established root system removes water from a soil root zone is approximately uniform down to about the wilting percentage. In this statement the interpretation of 'about' and 'wilting percentage' is somewhat variable. If by 'about' is meant 2 or 3 percent of soil moisture then in many cases this moisture-content range covers the major part of the soil-moisture tension range over which plants can grow. In the rest of the moisture range above and below field capacity, soil-moisture tension changes only slowly with soil-moisture content because of the hyperbolic nature of the soil-moisture-release curve. Also, the wilting condition of plants, both temporary and permanent, corresponds to an appreciable range in soil moisture content. In the field, on successive days temporary wilting occurs during an increasing fraction of the diurnal cycle and merges indistinguishably into a range of permanent-wilting stages as has been pointed out by several investigators. Throughout the moisture-depletion process the soil-moisture stress increases continuously, and much experimental evidence

supports the hypothesis that the growth rate of various plants decreases markedly in the available soil-moisture range and that vegetative growth is completely inhibited by the time the soil moisture is depleted to the permanent-wilting range."

6. SOME PLANT-SOIL-WATER RELATIONS IN WATERSHED MANAGEMENT

Leon Lassen, Howard W. Lull, and Bernard Frank. 64 pp. U. S. Dept. Agr. Cir. 910. 1952.

"The depth to which evaporation from a bare soil extends depends on soil porosity and depth to water table. On fine-textured upland soils where the water table does not influence evaporation, water losses are generally limited to the first foot of soil. Coarse-textured soils and cracked soils possess more and larger avenues for escape of the vapor particles, and here evaporation may remove water from depths as great as 5 to 6 feet."

"Where the water table lies close to the surface so that capillary flow feeds water to the surface for evaporation, soil porosity again is the limiting factor, but this time in relation to the movement of water in its liquid state rather than in its vapor state. Since small pores conduct capillary water farther than large pores, evaporation from fine-textured soils affects water tables to greater depths than in coarser-textured soils. For a coarse sand the limiting depth is about 14 inches; for a clay, 3 to 4 feet [Penman, 1946]. Thus, in areas where evaporation opportunity is great because of high water tables, the depth to which evaporation is effective is greater in clay than in sand; whereas in upland soils, where water tables are not a factor, the reverse applies.

"The amount of water evaporated varies not only with temperature and wind movement, but also with the supply of available water (evaporation opportunity). This factor outweighs all others. Even during the high temperatures of summer, evaporation losses will be no greater than during the cooler winter months if the soil is not frequently wetted by rainfall. During winter, when the soil is usually at or near field capacity, evaporation rates will be limited, not by the supply of water, but by conditions due to low temperatures."

"...The rate at which roots extract moisture decreases as soil-moisture content is decreased, or, in relation to energy, when increased force is required to overcome the attraction of moisture to the soil

particle. When moisture becomes available at a certain depth, as at the surface following a light rain, the rate of extraction at this depth will be increased. During this time interval moisture extraction will continue at other depths, but at comparatively higher tensions and lower rates.

"The foregoing analysis indicates the operation of a governing relationship which tends to reduce the difference between the magnitudes of the forces involved in the extraction of moisture at the various depths. Thus at high moisture contents, soil moisture will be reduced more rapidly than at lower moisture contents, tending to bring the energy levels--and the moisture contents--together. Simply expressed: the higher the moisture content the faster the loss."

"These considerations point to some salient distinctions between transpiration and evaporation, particularly in connection with the manner in which they create available retention storage. One is that whereas transpiration removes water simultaneously throughout the entire depth occupied by roots, evaporation proceeds downward from the surface. Another is that by acting on a greater volume of soil, transpiration removes a greater amount of water in a unit of time than does evaporation.

"Given a soil in which evaporation and transpiration reach to equal depths, a comparison of water loss from a bare area (where water is removed only by evaporation) with that from a well-vegetated area (where transpiration is the principal agent) will show that water is removed more rapidly--that is, retention storage opportunity is created more rapidly--in the vegetated soil. But assuming no addition of moisture to either area, evaporation will eventually remove a greater amount of water because the evaporation process is not governed by the physiological factors which limit transpiration losses."

"It must be kept in mind, however, that comparisons between evaporation from a bare soil and transpiration serve merely to indicate the manner and magnitudes of water losses. Actually, large expanses of completely bare areas--where only evaporation operates--are uncommon. Where they do occur, as in arid regions, lack of water severely limits evaporation losses. Bare spots within sparsely vegetated areas have a hydrologic importance that is related more directly to the rate at which water can enter the soil surface than to evaporation losses."

7. PLANT AND SOIL WATER RELATIONS ON THE WATERSHED

Paul J. Kramer. Jour. Forestry 50 (2): 92-95. 1952.
(Reprinted by permission.)

"Since most of the water is lost from the leaves, and since there are large differences among species with respect to leaf anatomy and leaf area, differences in rate of water loss would also be expected."

"It is often supposed that trees bearing thick, heavily cutinized leaves have lower transpiration rates than trees bearing thin leaves, but this is not necessarily true. Trees bearing thick leaves actually often have higher transpiration rates per unit of leaf surface than those bearing thin leaves. According to data of Caughey [1945] Ilex glabra and Gordonia lasianthus, which bear thick, leathery leaves transpire more per unit of surface than poplar, which has thin leaves. Holch [1931] observed that bur oak and hickory transpire more per unit of leaf area than red oak and linden, which have much thinner leaves. Swanson [1943] found the transpiration rate of Ilex opaca to be higher than that of coleus and tobacco. He concluded that leaf structure is not a reliable indicator of differences in transpiration among species."

"It is generally assumed that pines lose less water than broad-leaved species. This is true in terms of water loss per unit of leaf area, but is not always true in terms of water loss per tree from trees of equal crown volume. During a careful comparison made in our laboratory, loblolly pine transpired much less rapidly than yellow poplar and northern red oak on a leaf area basis. The total leaf area of the pines was about three times that of the two hardwoods; hence the total loss per tree was higher for the pines. The crown volumes of the various species used in these studies were similar. Groom [1910] many years ago pointed out that conifers do not always have low transpiration rates and that they sometimes lose as much or more water per tree as hardwoods of similar size."

"Large seasonal variations in transpiration occur. Few measurements of transpiration of trees have been made over an entire growing season, but it is obvious that water loss increases rapidly in the spring as new leaves unfold. According to Weaver and Mogensen [1919] there is a gradual decline in transpiration during the early autumn before the leaves fall. In general, it is probable that transpiration reaches its maximum about the time maximum leaf area is attained, then decreases slowly as an increasing proportion of the leaves become senescent, and decreases very rapidly as leaf fall begins."

''Studies by Weaver and Mogensen [1919] and by Kozlowski [1943] indicate that winter transpiration of conifers is almost as low as transpiration from bare branches of deciduous trees, at least under some climatic conditions. This probably is at least partly because cold soil hinders water absorption by conifers in the winter. It is probable that in the autumn and during periods of mild winter weather, transpiration of conifers may be much higher than transpiration of bare deciduous trees.''

''Another factor affecting the amount of water removed by vegetation is the depth of root systems. Obviously the greater the volume of soil occupied by roots, the greater the volume of water removed. There are considerable differences among species in respect to depth of root systems, dogwood being a notably shallow-rooted species, while pines often send roots to a depth of many feet. In heavy soils where most of the roots are concentrated near the surface, species differences are probably of less significance than in well aerated soils where deep penetration is possible. In mature Piedmont forests the surface soil is completely occupied by roots regardless of the species, and age of stand is probably more important than species. In well aerated soils deep-rooted species often remove water to depths of many feet. Wiggans [1937], for example, found apple trees in Nebraska absorbing water from a depth of over 30 feet. Some herbaceous species, such as alfalfa, are also very deep rooted in certain soils and absorb water from considerable depths.''

''An important question is the extent to which rate of transpiration decreases as the soil dries. Veihmeyer and Hendrickson [1950] claim that water is equally available from field capacity down almost to permanent wilting, but there is some evidence that this is not always true, especially in clay soils. The forces with which water is held increases as soil moisture decreases; hence less absorption would be expected from dry soil than from soil at field capacity. Schopmeyer [1939] found that transpiration of pine seedlings decreased as soil moisture decreased, long before permanent wilting was reached. Kozlowski [1949] obtained similar results with oak and pine seedlings. Transpiration of oak was decreased less than that of pine, probably because the former had more extensive root systems. Colman [1949] reported that at San Dimas evapotranspiration rates were higher during the rainy season than at any other time, at least partly because of the higher soil moisture content at that season.

''The highest water losses occur from vegetation growing at the margins of streams and bodies of water where the roots are always in contact with soil wetted to field capacity or higher. In general,

decreasing soil moisture probably reduces the rate of water loss from a forest stand; and it is quite certain that the total water loss is higher where the soil is kept wetted nearly to field capacity than where it occasionally dries down nearly to permanent wilting.

"Soil temperature is a limiting factor on water absorption during the winter. Experiments by Kozlowski [1943] and by the writer [1942] show that cooling the soil greatly reduces water absorption by pine seedlings. Furthermore, there are differences between species, absorption by northern species being reduced less than absorption by southern species. It seems possible that in winter, other things being equal, a white pine stand might lose more water than a loblolly pine stand of similar age and density of stocking."

EVAPORATION

8. SOIL PHYSICS

L. D. Baver. 398 pp., John Wiley and Sons, Inc., New York. Ed. 2, 1948. (Reprinted by permission.)

[P. 247.] "Evaporation of water from any source can occur only when the atmosphere in contact with the water is not saturated with water vapor, if both air and water have the same temperature ....Any meteorological effect that tends to increase the vapor-pressure gradient away from the soil will increase evaporation."

Baver cites temperature, relative humidity, and wind velocity as climatic factors; soil moisture content, depth to water table, texture, aggregation, color, exposure, and mulch as soil factors.

"...An analysis of the evaporation data from 243 monthly records from 29 meteorological stations throughout the United States has indicated that evaporation from a free-water surface varies approximately with the square of the mean monthly temperature in Fahrenheit degrees [Baver, 1937]."

[P. 248.] "The degree of saturation with moisture is the most important soil factor affecting the amount of evaporation."

Fisher (1923) and Keen et al. (1926) show that rate is practically constant at high moisture contents.

9. DRAINAGE AND EVAPORATION FROM FALLOW SOIL AT ROTHAMSTED

H. L. Penman and R. K. Schofield. Jour. Agr. Sci. 31: 74-109. 1941.

"In winter the soil does not dry at the surface. Winter evaporation is, therefore, much the same as would be obtained from a water surface and extra rainfall does not affect it."

"In summer the surface remains moist only a short time after rain has fallen; the air gradient is then much steeper than in winter. For the rest of the time the surface is drier and there is also a vapour pressure gradient in the soil. Hence (1) there is more rapid evapora-

tion while the surface is wet, (2) the total amount of evaporation is dependent upon both total rainfall and its distribution in time, (3) the later stages of evaporation are more dependent upon soil conditions than on air conditions, and (4) the total evaporation is much less than from open water."

10. LABORATORY EXPERIMENTS ON EVAPORATION FROM FALLOW SOIL

H. L. Penman. Jour. Agr. Sci. 31:454-465. 1941.

Penman determined water loss from a clay loam and sandy soil packed in 12-inch-deep cylinders under two treatments: (1) isothermal, when air and soil temperatures were equal; (2) non-isothermal, when soil surface was heated about 10 $^{\circ}$ C. above air temperature (typical June condition) by a 750-watt electric radiator suspended 2 feet above the soil surface for 8 hours a day.

In the isothermal treatment, soils lost moisture at a unit rate equal to that of open water until surface drying was apparent. With radiated soils, moisture loss was rapid for 2 days; "Thereafter the rate of loss is nearly constant and there is clear-cut evidence of conservation as compared with isothermal evaporation."

"Cumulative evidence suggests that some equilibrium is eventually attained whatever the nature of the initial behaviour, and that the differences between isothermal condition, intermittent radiation, and mulching lie in the rapidity with which this equilibrium rate is attained and the gross amount of water lost in attaining it."

"The result of an incomplete survey of the annual cycle of soil surface and air temperatures indicates that conditions may be regarded as isothermal when the mean air temperature is below 48 $^{\circ}$ F. and as non-isothermal above 48 $^{\circ}$ F...Thus the broad difference between winter and summer evaporation is that between isothermal and radiated condition."

From these experiments Penman assumed "that the action of radiation, or of very high temperature, is to dry out a shallow layer at the surface more quickly than it can be replenished by liquid flow from below."

"The liquid movement depends upon the capillary conductivity and the suction gradient, both being functions of moisture content; the vapour movement depends upon the relative humidity of the soil air and this is not nearly so dependent upon moisture content as the liquid variables are."

11. SOME ASPECTS OF EVAPORATION IN NATURE

H. L. Penman. Roy. Col. Sci. Jour. 16:117-129. 1946.

"...In the Rothamsted clay soil, there is little or no water movement from a water table lying at 3 or 4 feet below the surface, and for the coarse sand the limiting depth is about 14 inches. Water tables below these limiting depths (i. e., measured from the surface of bare soil or from the lower limits of plant roots in a cropped soil) will thus make no significant contribution to the soil as a source."

Concerning factors affecting evaporation: "In summer the most important factor is rainfall; the more often the soil is wetted the more evaporation there is. In winter, rainfall is unimportant because the soil is wet, and further rain cannot increase the wetness. The winter evaporation tends to remain constant...."

Plotting mean saturation deficit by months against mean evaporation per day by months "...shows that evaporation from bare soil is almost completely independent of air conditions in summer, but is greatly dependent on these conditions in winter.... In summer, the surface temperature of bare soil considerably exceeded air temperatures...."

"...Water movement in soil with even a slight moisture deficit is extremely slow, even with very great moisture gradients. As the deficit increases, the reluctance to move increases enormously. Drying conditions at the surface of bare soil, initially holding as much water as gravity will permit, tend to set up a liquid movement from below the surface. If the drying rate is small, the flow of water will be able to keep pace with it, and a steady drying rate will be maintained in which the soil surface behaves very nearly as if it were an open water surface...If the drying rate is rapid, the flow of soil water cannot keep pace with it, and the top layer of soil will dry, even although completely moist conditions exist only a few millimeters below...The result is that evaporation takes place, not at the soil-air surface, but a few millimeters

below, and the vapour has to diffuse through the dry soil before reaching the sink, thereby adding considerably to the total path of molecular diffusion and reducing subsequent evaporation rates to very small amounts."

"Surface hoeing, other than that necessary for killing weeds, is a redundant operation as far as moisture conservation is concerned; by the time the land is dry enough to be cultivated the sun has done the job."

12. FACTORS AFFECTING THE EVAPORATION OF MOISTURE FROM THE SOIL

F. S. Harris and J. S. Robinson. Jour. Agr. Res. 7(10): 439-461.

In laboratory experiments, evaporation increased with the initial quantity of moisture in the soil. The increase was not so great with higher percentages as with lower, and there seemed to be a number of critical points when the rate of loss changed rapidly. When the soils were saturated, evaporation was higher from finer soil particles than from coarser, but the differences were not marked. The rate of evaporation from a moist soil very rapidly decreased as air humidity increased. Air currents greatly increased evaporation, but after a velocity of about 10 miles per hour was reached, further increase was slight. Reducing the intensity of sunshine greatly reduced the rate of evaporation, as did slight reductions in temperature.

Compacting the soil (loam) in 2-inch layers gave greater evaporation. Soils compacted in the first and second 2-inch layers lost more heavily than soils with packed layers farther from the surface.

13. THE EFFECT OF FREEZING ON SOIL MOISTURE AND ON EVAPORATION FROM A BARE SOIL

Henry W. Anderson. Trans. Amer. Geophys. Union 27(6): 863-870. 1946. (Reprinted by permission.)

"At Northfork, California, where nightly freezing and daily thawing of the bare soil frequently occurred, it was observed that

during rainless periods of from one to three weeks the surface half-inch or so of the soil would become and remain very wet--near the liquid limit of plasticity. A study of the soil-moisture data and the associated soil freezing was made to determine what effect freezing had on the soil moisture in the profile and on evaporation from the soil."

"...The soil was an immature gravelly, sandy-clay loam of the Holland series....Soil-moisture samples were taken from under the brush and from a 14-foot square plot that was kept bare of vegetation and trenched annually to prevent entry of roots from the surrounding brush vegetation, which was 20 ft. distant from the bare area."

"By selecting early winter periods, before the soil profile had become wetted through, it was possible from successive soil-moisture samplings to study the changes in the moisture content for various depths. Since during these periods the deeper depths of the soil were warmer than the upper layers, movement of liquid moisture and vapor in the soil was upward, and no downward losses of moisture from the soil occurred. These were the only periods when evaporation losses could be determined with certainty by soil-moisture sampling.

"The results for a bare soil showed a rapid and relatively large upward movement of water and large evaporation losses during freezing periods....The daily depth of freezing varied from 0.1 to 0.7 in., averaging 0.44 in. For the ten-day period, net water losses from the soil profile by foot depths were: from the zero- to 12-inch layer, 0.24 in.; from the 12- to 24-inch layer, 0.17 in.; from the 24- to 36-inch layer, 0.53 in.; and from the 36- to 48-inch layer, 0.08 in. Therefore, the net evaporation loss from the bare soil for the period was 1.02 in. of water, over one-half of which had been drawn upward from the 24- to 36-inch depth. The moisture content of the 30- to 36-inch layer was reduced to less than nine per cent, despite the fact that the moisture equivalent of this soil was 16 per cent (the permanent wilting percentage was six per cent). Of the 9.13 in. of water in the soil at the start of the period, 4.47 in. were required to satisfy the wilting percentage, leaving 4.66 in. available for plant growth. The ten-day evaporation of 1.02 in. amounted to a loss of 22 per cent of the total amount of water available for plant growth.

"In contrast to these results from a bare soil, no freezing occurred under the brush-covered area during the same period, and there the transpiration-evaporation loss of water from the soil profile amounted to only 0.25 in. Free water-surface evaporation from a standard

Weather Bureau pan was only one-twelfth of the loss from the bare soil--only 0.08 in. for the period."

"The second method of study permits evaluation of the effect of freezing on the surface soil moisture during the whole winter period, and offers a means of estimating evaporation losses affected by freezing.

"The method includes: (1) Determination of the relationship of soil moisture to various climatic factors, including freezing; (2) expression of the change of soil moisture as a function of time following a rain, when freezing was zero. This change equals the evaporation rate, with certain limitations as to the length of the period to which it can be applied; (3) expression of the evaporation rate as a function of the soil-moisture content. From this the evaporation rate and total evaporation during an interval is expressed as a function of the climatic factors, including freezing. The last is based on the assumption that as freezing affects the soil-moisture content, the evaporation rate in turn is affected; (4) comparison of the evaporation as determined by the equations with the actual measured evaporation."

The author developed regression equations predicting total evaporation during freezing and non-freezing periods. The actual and calculated evaporation values were as follows:

Dates	Bare soil				Brush-covered soil, without freezing, actual values	Free water surface
	With freezing		Without freezing			
	Actual	Calculated	1/ Actual	Calculated		
	Inches per day					
Jan. 9-19 1939	0.10	0.09	0.03	0.03	0.025	0.008
Dec. 20-31 1937	.09	.10	.03	.03	.025	.008

1/ Not for the same periods, but for similar 6- to 10-day periods.

In a discussion of the mechanism of water movement upward during soil freezing, the author points out that vapor movement due to vapor pressure and thermal gradients would account for only a small part of the movement.

"Movement under tensions set up in the water films adjacent to the ice crystals seems most probably to be the principal mechanism. An indication of the magnitude of such tensions is obtained from the freezing point depression (3^{o}C). According to an equation given by ANDERSON, FLETCHER, and EDLEFSEN [1942], if it is assumed that the ice freezes out at one atmosphere pressure, the adjacent water is under a tension of 36 atmospheres. Under such tension the water could be expected to flow through the connected water films which extend downward into the soil."

14. SOME FACTORS AFFECTING THE EVAPORATION OF WATER FROM SOIL

C. A. Fisher. Jour. Agr. Sci. 13: 121-143. 1923.

Fisher describes four stages of drying evident when rates of drying are plotted against moisture content. At high moisture contents, no change in rate for evaporation takes place from a free water surface. Then the rate breaks off from the horizontal and drops sharply, becoming proportional to water content. In the third stage, rates drop off because of the influence of capillarity, and because the rate of water movement from within the soil is less than the rate of surface evaporation. In the final stage, the curve bends to the origin, evaporation diminishing as adsorbed water is given off.

Clay, silt, and loam all had drying curves of somewhat different shapes. "The moisture contents at which the rates of evaporation begin to fall off, i.e., at which the vapour pressure of the retained moisture begins to diminish, are characteristic for each soil. They are some function of the total surface of the soil grains which in turn is dependent on the average size of the grains. This water content may therefore be used as a means of characterizing soil."

15. THE MOVEMENT AND EVAPORATION OF SOIL WATER IN RELATION TO pF

C. M. Woodruff. Soil Sci. Soc. Amer. Proc. 6:120-125. 1941. (Reprinted by permission.)

"Small jelly tumblers were filled with soil, saturated with water and set in the laboratory to dry. One set of samples were exposed to the still air of the laboratory, the remainder were placed before an electric fan. The relative humidity was near 50% and the temperature fluctuated between 24° and 28° C. Tumblers of water were intermingled with the tumblers of soil. All were weighed at intervals to observe the quantity of water lost from the soil in relation to the quantity lost from the free water surface. The loss from the free water surface was used as a functional measure of time. The soils studied included white sand uniformly 0.08 mm. in diameter, sandy loams, silt loams, and clay loams. The latter two were granulated and of good tilth."

"A typical curve expressing the quantity of water evaporated from the soil with respect to time...possesses two distinctly different components. The rate of evaporation from the soil was constant and slightly less than the evaporation from the free water surface during the initial stage. This stage was followed abruptly by a much slower rate of evaporation that decreased regularly with time. The transition from the initial stage to the final stage occurred at a moisture content that coincided with a moisture potential of pF3...The surface of the soil was moist in appearance before the transition. It began to dry at the point of transition and as evaporation continued, an abrupt dry moist boundary moved deeper into the soil. Similar phenomena were observed when the soil was exposed to stagnant air. However, the rate of evaporation in still air was one-tenth of that in moving air and the transition between the two portions of the curve was less abrupt.

"Similar results were obtained for other soils. The outstanding features of this study were the formation of a dry crust on the surface of the soil and the transition in the shape of the evaporation curve at pF3 for fine sandy loams, silt loams, and granulated clay loams. Interpreted in terms of the previous results for sand of uniform particle size, the results indicate that in the graded system of pore sizes, water will move as a liquid by capillarity below pF3 and as a vapor by diffusion above pF3."

''Six highly weathered soils...puddled upon wetting. These soils failed to show a well-defined boundary between the dry surface and the moist soil beneath. Moisture continued to move in the liquid phase from these soils at moisture potentials above pF3. Movement of water as a liquid at moisture potentials above pF3 may occur in soils dominated by pore sizes that are small enough for the adsorptive forces to stabilize the contents of the pores at high curvatures of the air water interface.

''The moisture content of the soil beneath the dry surface crust corresponded closely with that at pF3 in 16 of the 27 soils studied. Results comparable to these are to be expected for the majority of the medium-textured soils of good tilth, because the dominant group of pore sizes in these soils falls within the range where surface tension forces impose a condition of instability on the water within the pores.

''Movement of water through the soil in the liquid phase ceases when the surface of a short column of soil becomes dry. Water loss may then occur only by evaporation beneath the surface, and the rate of evaporation is related inversely to the square of the thickness of the dry layer of soil through which the vapor diffuses. Practically, this means that it will require four times as long to dry out the second inch of soil as it does to dry out the first inch.''

16. EVAPORATION FROM SOILS AND TRANSPIRATION

F. J. Veihmeyer. Trans. Amer. Geophys. Union 19:612-619. 1938. (Reprinted by permission.)

''Since the motion of water at moisture-contents lower than field-capacity is slow, it would seem that the rate of movement to the surface and hence the rate of evaporation-loss would be small. Our experiments show that the loss of moisture by direct evaporation from the soil-surface [clay loam] is largely confined to a shallow surface layer of about eight inches. Furthermore, the evaporation-loss has been shown to be very small compared to the amount of water taken from the soil as transpired by plants.''

''Some of the tanks with bare uncultivated soil were kept under observation for long periods but were covered during rains so that no water was applied to them after the beginning of the tests. One of the tanks lost only 57 pounds of water during four years of exposure to

evaporation and still there was moist soil below the top foot. Thus, 57 pounds loss, which is 18.9 pounds to the square foot of surface exposed to evaporation, is equivalent to a depth of about 3-3/8 inches of water for a period of four years."

"When the soil is in contact with the free water-surface losses of water by surface-evaporation may be greater than those just indicated. Table 1 gives the average evaporation from water-logged soils at Davis, expressed in inches per day. Depth to the water-table is indicated in the first column. Depths were maintained by automatic water-level regulators. It is interesting to note that the loss of water by evaporation from soils with a water-table at 0.5 foot from the surface is about the same as the average use of water by many agricultural plants. Also, it is interesting to note that with the water-table at about four feet from the surface, the loss by surface-evaporation is approximately one-hundredth of that from soils with a water table at 0.5 foot; or in other words, the transpiration-losses of water through plants, is as much in one day as that which would occur by surface-evaporation from soils with a water-table at four feet in about 100 days."

Table 1.--Average evaporation from water-logged soils at Davis [Calif.]

Depth to water	1936	May 15 to Sept.1, 1937	Mar. 29 to Nov. 10, 1937
feet	inch/day	inch/day	inch/day
0.0	0.328	0.317	0.216
0.5	0.215	0.230	0.182
1.0	0.209	0.194	0.162
1.5	0.093	0.086	0.076
2.0	0.079	0.055	0.051
3.0	.....	.....	0.026
4.8	.....	.....	0.016

17. EXPERIMENTS TO DETERMINE RATE OF EVAPORATION FROM SATURATED SOILS AND RIVER-BED SANDS

Ralph L. Parshall. Trans. Amer. Soc. Civ. Engin. 94:961-999. 1930. (Reprinted by permission.)

"The cooling effect of the rain on the soil increases the surface tension of the capillary moisture drawn up from the water-table. Rain water falling on the soil also dilutes the soil solution and if the solution is alkaline it increases the rate of evaporation. It is evident that, although adding moisture to the soil at the time, light showers may later cause a more rapid depletion of the moisture already within the soil."

Soil tanks with water tables 12 inches below the surface were sprinkled in quantities approximating a shower of rain. Evaporation loss increased materially. For one tank the ratio of loss compared with that from free water surface was 32 percent during the unsprinkled period and 76 percent during the sprinkled period; for another tank comparable values were 11 and 33 percent, respectively.

18. RAINFALL, RUNOFF AND SOIL MOISTURE UNDER DESERT CONDITIONS

Forrest Shreve. Ann. Assoc. Amer. Geog. 24(3):131-156. 1934. (Reprinted by permission.)

Soil-moisture determinations were made in Arizona in the alluvial clay, or abode, of the Santa Cruz floodplains and on the adjacent bajada soil.

"It is obvious...that the winter rains are far more effectual than the summer ones in building up the moisture of the soil. This is due in part to the high runoff that has been shown to characterize the summer rains, and in part to the much more active evaporation from the soil surface at that season. Of the six rainy seasons comprised in the period of observation there was only one which influenced the moisture below 60 cm., its effect extending to 150 cm. It is evident that much of the water which enters the soil is destined to return by the same path and never to reach the lower levels of higher moisture, where a long capillary journey protects the moisture from possibility of evaporation. There is abundant a priori evidence that the moisture of the lower levels is more securely maintained by the existence of a dryer soil above. There is also

evidence in the present work that a profound wetting such as the soil received in the winter of 1931-32 may do more to reduce than to increase the moisture of the lower levels. It will be noted that the moisture at 180 cm. stood at 15-16% from September, 1930, until May, 1932, and that the same percentage was sometimes found at 150 cm. Following the heavy wetting of the winter, 1931-32, the moisture at 180 cm. fell to 13-14% and with various aberrancies has stood at that percentage ever since. It is highly probable that this permanent fall was due to the establishment of a better system of capillary films from 180 cm. to the surface than had existed for some time, and that the lower levels of the soil lost water more rapidly through their existence than had been possible under the dry surface conditions of the previous 20 months."

"The depth of the alluvial clay places a large store of water at the disposal of the mesquite, the roots of which sometimes penetrate to a depth of 10 meters. The shallowness of the volcanic clay limits the extent of the good moisture supply available to the plants of that soil. The low range of moistures in the bajada loam, together with the almost universal occurrence of caliche in the outwash of volcanic hills, renders the conditions severe for plants and permits only the open occurrence of the most drought-resistant shrub of the region. The march of soil moisture conditions seems, therefore, to be one of the most important conditions differentiating the vegetation in a region in which securing an adequate water supply is the most immediate problem of all plants."

19. STUDIES ON SOIL TEMPERATURES IN RELATION TO OTHER FACTORS CONTROLLING THE DISPOSAL OF SOLAR RADIATION

R. K. Dravid. Indian Jour. Agr. Sci. 10: 352-387. 1940.
(Reprinted by permission.)

"Weekly determinations of soil moisture [black cotton soil] at depths of 0.2 in., 4 in., 6 in., 8 in., 12 in., and 18 in. were made from the middle of July, 1935, on the bare plot of the Central Agricultural Meteorological Observatory. The data up to the end of November 1936, i.e., over a period of about sixteen months... illustrate the variation of moisture both with depth and with time."

During rainy spells the soil had a high moisture content throughout the upper 18 inches."... During the frequent breaks in the monsoon rains at Poona, the moisture content fluctuates rapidly in the first six inches of the soil. After the withdrawal of the monsoon the surface layers of the soil are subjected to more or less unbroken dessication during the long spell of dry weather extending from the first week of November 1935 to the beginning of June 1936."

After the initial desiccation the soil moisture content remained nearly constant during the dry season, 5 percent near the surface and 25 percent at a depth of about 1 foot. This illustrates the protecting influence of the dry surface soil on the layers below.

20. CHANGES IN SOIL MOISTURE IN THE TOP 8 FEET OF A BARE SOIL DURING 22 MONTHS AFTER WETTING

R. H. Hilgeman. Jour. Amer. Soc. Agron. 40: 919-925. 1948. (Reprinted by permission.)

Observations were made in the Salt River valley, Arizona. The soil was Cajon silt loam--a bare area, kept free of weeds. The distance above the water table was 65 to 70 feet.

"...Between May 1 and Nov. 1, 1944, when the soil moisture content was relatively high, 5.69 inches of water were lost from the upper 8 feet. The effect of moderate showers in May and July could not be detected from the samples obtained. Between Nov. 1, 1944, and Mar. 29, 1945, rainfall added to the amount of water in the upper 2 feet of soil. During this interval no significant changes occurred in the moisture content of the soil in the 24- to 96- inch zone. Beginning May 1 and extending to November 1, 1945, 2.59 inches of water were lost."

Decrease in moisture content during 22-month period

Depth (in.)	Loss (in.)	Available water lost (percentage)
0-12	1.35	67
12-24	1.51	75
24-36	2.42	75
36-48	1.72	78
48-60	1.39	51
60-72	0.66	20
72-84	0.54	18
84-96	0.24	10

"The rate of loss of water appeared to be related to temperature and the moisture content of the soil....More water was lost during the first summer than during the second. Assuming the temperatures were equal, the rate of loss was a function of the moisture content of the soil."

21. FOREST INFLUENCES

Joseph Kittredge. 394 pp. McGraw-Hill, New York. 1948. (Reprinted by permission.)

From the author's summary of influences of forest on soil evaporation, p. 156:

"Evaporation as measured by losses from soil surfaces is usually less than from free water or wetted instrumental surfaces, and the differences become progressively greater as the surface soil is drier.

"The depth to which evaporation is effective in lowering the free water level in initially saturated soils increases as the soil texture becomes finer from about 14 in. for coarse sand to over 32 in. for heavy loam.

"Water rises more quickly by capillarity in coarse- than in fine-textured soils, but the evaporation losses from any soil are extremely slow after the surface 8 in. becomes dry.

"Evaporation from bare soil decreases as the amount of moisture in the surface foot decreases and as the depth to the water table increases.

"Insofar as vegetation reduces wind velocity, it tends to reduce evaporation also and in proportion to its density."

"The evaporation from soil covered by forest floor is 10 per cent to 80 per cent of that from bare soil. The reduction varies with the kind of floor and increases as the floor becomes thicker at least up to a thickness of 2 in.

"The evaporation from water or wetted surfaces is decreased by vegetative cover progressively more by mesophytic and climax than by xerophytic and preclimax types; more by dense- than by light- crowned species; more by tolerant than by intolerant species; more by well-stocked than by understocked stands; more by stands near the physical rotation age than those older or younger; and more by deciduous than by evergreen species during the warm season."

TRANSPIRATION

22. TRANSPIRATION AND TOTAL EVAPORATION *

Charles H. Lee. Physics of the Earth--IX. HYDROLOGY, pp. 259-330. Dover Publications, Inc. New York. 1942.

[Pp. 273-274.] "The relative advantages and disadvantages of transpiration have been the subject of much debate, the extreme positions being (1) that the process is an unavoidable evil and (2) that it is vitally important to the normal functioning of the plant organism. Among the arguments in support of the second position is that transpiration cools the leaves and prevents injury or death by high temperatures. Experimental work has shown that the degree of cooling rarely exceeds 2^{o} to 5^{o} C., which, in view of the present state of knowledge of protoplasm, could be of little aid in preventing injury from heat (Miller, 1938). The death of leaves in hot weather is apparently due to excessive loss of water from protoplasm rather than excessive increase in temperature.

"Another argument is that transpiration increases the rate of absorption from the soil of inorganic salts that are required for plant food. It has been proved conclusively, however, that there is no relation between rate of transpiration and absorption of mineral salts from the soil (Miller, 1938). It is also seriously questioned whether the transpir ation stream aids materially in transporting absorbed salts from roots to leaves, leading authorities stating that transpiration can have little or no effect upon the movement of nutrients (Miller, 1938). Viewed in all its aspects, transpiration is unquestionably a very wasteful process, and its harmful effects upon plant life appear to exceed by far its beneficial effects. The benefits, if any, do not compensate for the elements of danger.

---

* Reprinted through permission of Dover Publications, Inc. and the National Research Council, from HYDROLOGY by O. E. Meinzer, Dover Publications, Inc., N. Y. ($ 4.95)

"It has been pointed out (Barnes, 1902) that the explanation of this anomalous condition may be found in the origin and development of the transpiration process. Probably in the primitive stage plants lived in water and derived the carbon dioxide and oxygen needed in the process of photosynthesis and respiration directly from this source. As development took place plants have not materially changed their method of obtaining these gases. As at present organized, with foliage exposed to the atmosphere instead of to water, wet cell walls are exposed to drying by evaporation as well as absorption of carbon dioxide, and except under special conditions have developed no effective means of protection against loss of water. Transpiration, although a constant source of danger to plant life, is thus unavoidable and must be recognized in any study of the hydrologic balance."

23. INFLUENCES THAT AFFECT TRANSPIRATION FROM PLANT LEAVES

Burton E. Livingston. Sigma Xi Quart. 26: 88-101. 1938. (Reprinted by permission.)

Livingston notes the distinction between two kinds of foliar transpiration, cuticular and stomatal.

"Two kinds of foliar transpiration are to be distinguished, cuticular transpiration and stomatal transpiration. In cuticular transpiration vaporization of water occurs just at the leaf periphery (from the cuticle and from trichomes of hairs, if present) and the water vapor produced escapes to the surrounding air as it forms. In stomatal transpiration, on the other hand, vaporization occurs at the peripheries of the substomatal chambers, into the internal atmosphere of the leaf, and the water vapor thus produced diffuses subsequently through open stomata into the surrounding air.

"The fundamental driving pressure of cuticular transpiration is just the vapor pressure at the exposed surface of the liquid water held in the ultra-microscopic pores of the cuticle. Other conditions being constant, it is of course greater as foliar temperature is higher, and conversely. Because of the wax-like nature of cuticle and its low water content even when saturated, cuticular vapor pressure never approaches in magnitude the corresponding vapor pressure of a free surface of pure water, or of aqueous solution like the solutions within the cells and vessels. Cuticular transpiration from a leaf surface is therefore generally much slower than stomatal transpiration when open stomata are frequent, but it is often relatively important when stomata are sparse or predominantly closed."

"The driving force of stomatal transpiration is the vapor tension of water vapor in the substomatal chambers. It is commonly greater than the vapor tension of the outside air but not as great as the vapor tension of water-saturated air at the same temperature. Its magnitude depends on the rate of outward diffusion of vapor into the outside air and on the vapor pressure of the imbibitionally wet cell-wall surfaces that surround the chambers; in health these surfaces are regularly free of superficial liquid."

"The internal influences that affect the transpiration rate directly may be usefully summarized as: (a) the area of the leaf surface, (b) the water-vapor pressure of the cuticle, (c) the frequency of stomata, (d) the average size (or diffusive capacity) of the stomatal openings and (e) the vapor tension in the substomatal chambers. Both the vapor pressure of the cuticle (its tendency to drive water vapor into the air by cuticular transpiration) and that of the cell walls about the substomatal chambers (their tendency to drive water vapor into the chambers and outward through open stomata) are dependent on the nature of the surfaces involved and upon their temperature, as well as on their relative degree of wetness, and also upon the current rate at which heat from absorbed radiant energy is being received at the vaporizing surfaces without corresponding rise in temperature. Wetness of walls or cuticle naturally depends partly on the previous rate of water renewal and partly on the previous rate of vaporization therefrom. The influences of absorbed radiant energy, air temperature, air humidity and air movement are to be considered as external influences."

"The only external influence that affects transpiration directly is the resistance offered by the adjacent layer of external air. But air movement generally tends to reduce that resistance, by continually replacing the adjacent air layer with drier ambient air, while absorbed

radiation and air temperature influence the vapor pressure of the leaf surfaces. Therefore air movement, the temperature and vapor tension of the ambient air and the drying effect of sunshine are commonly considered as the external influences that take part—although indirectly—in the determination of transpiration rates."

"The sweeping influence of wind, to accelerate transpiration, is always of very great importance, but its mechanical influence (as wind pressure bends and waves plant leaves to and fro and too alters their exposure) is not to be neglected in this connection."

"The pronounced and rapid changes of light intensity that commonly occur in early morning and in late afternoon often exert a very great indirect influence on transpiration through the photeolic responses of motile stomata. The stomata of many plants open in the morning because of increasing light intensity and close in the evening because of decreasing light intensity. The complex mechanisms by means of which these photeolic responses are brought about need not be considered here further than to remark that the turgor of the stomatal guard cells increases with the increasing light intensity of early morning and decreases with the decreasing light intensity of early evening, and that the opening and closing movements are due to turgor increase and decrease, respectively. But turgor alterations in guard cells are occasioned also by non-photeolic changes in the water relations of these cells and the neighboring tissues, and stomatal movements are therefore not always to be explained by reference to alterations in light intensity. Motile stomata frequently show closing movements in the daytime with advanced stages of incipient drying.

"It is clear that outward diffusion of water vapor from the substomatal chambers must be greatly retarded when most of the stomata are closed and when the vapor tension of the outer air does not at the same time greatly retard that diffusion. An idea of the general manner in which motile stomata may alter throughout a clear day may be had from the following approximate averages of length and width of the nearly elliptical cross-sections of stomatal openings on the lower surface of a mature leaf of August lily. Dimensions are given in thousandths of a millimeter."

Hour of observation	4:30 AM	5:30 AM	10:00 AM	3:00 PM	6:30 PM	12:30 PM
Length [of opening]	1.4	3.6	6.5	11.0	1.1	1.0
Width [of opening]	.6	1.1	1.3	1.5	.3	.3
Average elliptical perimeter	2.0	4.7	7.8	12.5	1.4	1.3

''When incipient drying of the leaf tissues induces sufficient closing movement in motile stomata, stomatal transpiration is thereby retarded in another way. Thus stomata frequently attain their maximal degree of opening for the day, and begin to close, long before light intensity begins to decline. This early closure, which is not photeolic, appears to be of general occurrence, but it is naturally most pronounced when transpiration is unusually rapid or when the leaf is inadequately supplied with water. Motile stomata generally begin to close in the daytime long before wilting becomes apparent.''

24. STUDIES OF EVAPORATION AND TRANSPIRATION UNDER CONTROLLED CONDITIONS

Emmett Martin. Carnegie Inst. Wash. Pub. 550. 1943. (Reprinted by permission.)

Helianthus annuus (sunflower) and Ambrosia trifida (ragweed) were grown in cans holding about 1 kilogram of sandy loam at field capacity. The correlation between rate of transpiration and relative humidity in darkness in calm air was investigated at temperatures of 27, 38, 49° C. The youngest plants tested were 34 days old; the oldest, 84.

''For young plants, the relation between transpiration rate and relative humidity was approximately linear at all three temperatures, although at 49° there was a tendency for the rates at low relative humidities to fall below the values expected from the straight-line relation.

''For older plants, the rate of transpiration at 27° was less than for the young ones, but the relation with relative humidity still appeared to be linear. At 38°, however, the older plants showed lower rates of water loss than the young ones only for relative humidities below 50 per cent. Above this point, no difference was detectable. At 49° no difference between young and old plants was observed at any relative humidity. These differences between young and old plants are probably due to dependence of permeability of protoplasm on age and temperature.

''The influence of wind on rate of transpiration increased considerably with temperature, probably because of an increase in the cuticular component of transpiration. Exposure to wind of 250 cm/sec.

at high temperatures and low relative humidities sometimes resulted in closure of the stomata in less than 3 minutes."

"The ratios of nighttime to daytime transpiration rates of Helianthus annuus under constant conditions in darkness were found to be 0.64, 0.67, and 0.91 at air temperatures of 27°, 38°, and 49° C. respectively, indicating a reduction in the regulatory power of the stomata at high air temperatures. This behavior is probably due to an increase in the cuticular component of transpiration at high leaf temperatures.

"The maximum temperature depression of leaves observed in these experiments was 20° C. Ordinarily transpiration produced cooling of only 10° C. or less. The depression of the temperature of the leaves below that of air for a given rate of transpiration per unit leaf area decreased with increasing leaf temperature. This result could be explained as due to an increase in the wetness of the epidermal surface, which indicates an increase in the permeability of the cuticle and epidermal cell walls to water.

"The influence of visible radiation on the transpiration rate of single attached leaves of Helianthus annuus is linear. The accelerating influence of radiation is apparently about 25 percent greater than would be expected as a result of its effect in raising the leaf temperature. Presumably radiation has an effect on permeability of protoplasm independent of temperature."

25. ECOLOGICAL ASPECTS OF TRANSPIRATION

I. Pike's Peak region: climatic aspects.
II. Pike's Peak and Santa Barbara regions: edaphic and climatic aspects.

Charles J. Whitfield. Bot. Gaz. 93(4): 436-452 and 94 (1): 183-196. 1932. (Reprinted by permission.)

Sunflower, wheat, and corn were used as phytometers in four climatic formations to obtain a measure of transpiration under various climatic factors.

The plants were grown in water-proofed cylinders 9 inches tall and 5.5 inches wide. The plants were watered, and the containers

weighed and sunk in ground to the same level as native vegetation. The containers were left in ground for 2 - 4 days and then reweighed.

"In all cases transpiration decreased with increased altitude. This was true for all species used in the different series. Of the various climatic conditions measured, evaporation, soil and air temperatures, and saturation deficits decreased with increased altitude. On the other hand, the approximate values of the maximum intensity of radiant energy on a clear day were 1.48, 1.58, and 1.64 cal. per $cm.^2$ per min. for plains, montane, and alpine respectively, showing increased values with increased altitude. However, the total energy over a season might reverse these readings because of the more cloudy conditions in the alpine region. No data are at present available on this problem. Relative humidities, rainfall, and holard are usually greater at the higher elevations. Wind is constantly highest in the alpine region, with the plains next, and the montane zone ordinarily the lowest."

"A close relationship exists between transpiration, air temperature, and relative humidity, and between transpiration and a combination of these two factors. The average air temperature, relative humidities, and transpiration of the natural groups approximates a straight line. This relationship is strengthened by the fact that the average air temperatures, relative humidities, and transpiration at the main climatic stations indicate a straight line. While the results approximate a straight line between transpiration, air temperature, and relative humidity, such a correlation does not exist between transpiration, saturation deficit, and evaporation. The transpirational points which fall naturally on an approximately straight line with air temperature and relative humidity do not do so with saturation deficit and evaporation. These results show that the two curves of transpiration and saturation deficit do not run parallel. In addition, the mathematical ratios of transpiration and saturation deficit are irregular. The fact that the points do not approximate a straight line, as well as the irregularity of the ratios, indicates that saturation deficit does not bear so close a relation to transpiration as do air temperature and relative humidity."

"Experiments to determine the effect of various soil temperatures on transpiration were conducted at the Alpine laboratory during the summers of 1930 and 1931. Three conditions, cold, intermediate, and warm, with respective temperatures of 36°, 51°, and 113° F., were used for the initial experiment. Thirty standardized sunflower plants were divided into three groups of ten each, weighed and placed in the conditions already described. When reweighed, the batteries showed the following losses: cold, 19.0; intermediate, 46.2; and warm, 53.3 gm.

The results show a rapid rise of the transpirational curve with a comparatively low increase of soil temperature, and a flattening off of the transpirational curve with high soil temperatures. These results indicate, as does the initial experiment conducted in the alpine tundra, that when soil temperatures get above 40° F., they are not as important in influencing transpiration as they are below this temperature."

"In order to check the relation of different soil moistures to transpiration, sunflower plants were grown in a uniform soil and standardized. The plants were then divided into three groups, one set allowed to approach the wilting coefficient (or a low water content), another brought to medium content, and the third given a high holard. The experiment was conducted for a 5-day period, at the end of which time water contents were figured on the basis of dry weight and the osmotic values were determined.

"Water loss apparently increases with the water content until the optimum conditions are reached. In this experiment the highest water content gave a water loss below that of the medium, owing undoubtedly to poor aeration. Osmotic values showed a constant decrease with increased soil moisture."

26. DAILY TRANSPIRATION DURING THE NORMAL GROWTH PERIOD AND ITS CORRELATION WITH THE WEATHER

Lyman J. Briggs and H. L. Shantz. Jour. Agr. Res. 7(4): 155-212. 1916.

At Akron, Colorado, plants of 22 crops were grown in galvanized-iron pots containing about 115 kilograms of soil. The pots had tight-fitting covers with openings for the stems. Loss of water was limited to transpiration. The pots were weighed daily during the growth period, and water was added daily to insure an adequate supply.

"...The direct solar radiation received by the plants at Akron is usually not sufficient to account for the observed transpiration during the midday hours. In some of the small grains the energy dissipated through transpiration is twice the amount received directly from the sun. [This indicates the importance of indirect radiation.]

"The march of transpiration due to changes in the plant alone (change in the transpiration coefficient) may be expressed by the ratio of the daily transpiration to the daily evaporation if we assume the latter

to constitute a perfect summation of the weather conditions determining transpiration. The transpiration of the annual crop plants (aside from fluctuations due to weather) rises to a maximum a little beyond the middle of the growth period and then decreases until the plants are harvested. Perennial forage crops such as alfalfa increase steadily in transpiration to a maximum at or near the time of cutting. Various crops show their individuality by departing more or less from these types.

"The transpiration coefficient of many of the crops increases exponentially during the early stages of growth. Sudan grass, for example, doubled its transpiration coefficient every four days during the early growth period. Alfalfa throughout practically the whole period between cuttings doubled its transpiration every eight days."

"The correlation has been determined between the various physical factors of environment and the transpiration of the different crops, considered both individually and as one population. The correlation coefficients in the latter case for the season of 1914 are as follows:

"Transpiration with radiation, 0.50 ± 0.01; with temperature, 0.64 ± 0.01; with wet-bulb depression, 0.79 ± 0.01; with evaporation (shallow tank), 0.72 ± 0.01; with evaporation (deep tank), 0.63 ± 0.01; and with wind velocity, 0.26 ± 0.01."

27. THE TRANSPIRATION OF DIFFERENT PLANT ASSOCIATIONS IN SOUTH AFRICA

Part IV--Parkland; forest and Sour Mountain - grassveld; large Karoo bushes.

M. Henrici. Union So. Africa Dept. Agr. and Forestry Sci. Bul. 244. Pretoria, 1946. (Reprinted by permission.)

Transpiration was measured by weighing material cut from trees or plants.

"From a number of preliminary experiments it was observed that the transpiration of woody branchlets was constant for about 6 minutes after their removal from the tree; after the 9th minute, however, their transpiration dropped rapidly, corresponding to the closing of the

stomata (Henrici 1940). No increase in transpiration after cutting was observed. Gramineae showed a slowing down of the transpiration from about the 5th minute after they had been cut. It was therefore decided to take the reading of the first 3 minutes as the basis for the transpiration value.... Within a few seconds after cutting, branchlets were on the balance ready for weighing, which is important with this method."

"In an investigation on transpiration in Europe the factor of soil moisture would scarcely come into consideration. In South Africa soil moisture is a most important factor. <u>All xerophytes in South Africa so far investigated--succulents excluded--have a high transpiration power if exposed to the sun, so long as the soil moisture is adequate</u>.... In misty weather or rain no transpiration takes place."

"Of special interest is the effect of wind. Even in Europe there is still a controversy as to its effect on transpiration. In South Africa it never has an accelerating effect on the transpiration of trees; on the contrary, the stomata of all tree foliage close as soon as there is strong wind and the leaves therefore restrict transpiration almost immediately. On grass the effect is different. An accelerating effect is observed, but this does not last long, as after a while the aperture of the stomata is decreased and the transpiration <u>eo ipso</u> diminishes."

"Last, but not least, temperature and light have to be mentioned as external factors influencing transpiration. There is no doubt that for all the investigated associations the change from darkness to light increases transpiration, but a quarter of the intensity of sunlight is quite enough to ensure maximal transpiration. After 9 to 10 a.m. no further increase in transpiration, due to stronger light, could be recorded on clear days."

Regarding the daily trend of transpiration: "The maximum transpiration is not correlated with either the maximum light intensity, or with the maximum temperature, or with the minimum humidity, except on very wet days or early in spring. On the contrary, nearly all daily graphs have two maxima for transpiration--one before 11 a.m. and the other after 3 p.m. The midday depression of the transpiration was apparently observed in South Africa long before anything about it was published in Europe. The fact that it is not regularly observed in early spring or when the soil is really saturated, suggests that it is an automatic protective measure of the plant against excessive transpiration; in most cases the stomata are not fully open during the midday depression, yet they are not so much closed that they could be the only reason for the decreased transpiration."

"The noon depression of transpiration is doubtlessly connected with the decrease in free water in the leaves which is only replaced later in the afternoon or in the evening."

"It is clear that the factors restricting transpiration are very different in the various climates. In the Sour Mountain-grassveld or in the 'Ndema forest of the Drakensberg, the very high relative air moisture, often mist, causes 0 values, especially early in the morning. At Fauresmith the low moisture inhibits transpiration, this being particularly noticeable in the afternoon of hot summer days. In winter the temperature early in the morning usually depresses transpiration, presumably not as such, as radiation is strong enough, but by preventing a regular supply of water from the roots. In extreme cases real dormancy of the trees can be observed.

"If, broadly speaking, the potential transpiration (not the actual) of a tree in the Orange Free State is the same as for the same species or a near related species in the Drakensberg, it is eo ipso understandable that the espacement of trees in the dry climate must be very great."

28. TRANSPIRATION OF SOUTH AFRICAN PLANT ASSOCIATIONS

II. Indigenous and exotic trees under semi-arid conditions.
M. Henrici. Union So. Africa Dept. Agr. and Forestry Sci. Bul. 248. Pretoria, 1946. (Reprinted by permission.)

Henrici measured transpiration by determining the loss in weight of cut branches during a three-minute period beginning one minute after the branches were cut.

"Even on clear days, the light proved too weak after 5 p.m. for any appreciable transpiration, although the stomata were sometimes wide open. It seems that the transpiration of this botanical formation is more or less limited to nine hours of the day. This is readily understandable for the moist valley itself, but it is rather interesting for the slopes and ridges where the trees simply stopped transpiration about 5 p.m. with the disappearing, not setting sun."

"...Harder (1935) still considers the possibility, in an arid region, of wind having a beneficial influence on plant life in decreasing the transpiration by lowering the temperature of the plant and by causing

the closing of the stomata. Firbas (1931) points out that the first gust of wind always accelerates the transpiration which, in the case of more hardy plants, decreases after the primary increase and may therefore fall below the value obtained in calm air.

"To the author's mind these two points govern the transpiration of the trees in the semi-arid region of Klapperkop. If the wind is of any duration, there is certainly no increasing effect, but with single gusts there may be a momentary increase."

"Does the transpiration curve of the investigated trees follow temperature, air moisture and light intensity? The question has lately been answered in the affirmative for grasses at Pretoria (Mes 1935) where the lowest air moisture and highest temperature apparently coincided soon after 12 noon with the highest transpiration calculated as a percentage of the water content. The soil moisture was exceptionally high, being rather like laboratory than veld conditions. In the present investigation, which was made during the rainy season of a very wet year, the soil moisture was certainly as favourable as it could possibly be, although it is fully realized that the water content of shale soil will hardly exceed 20%, and that the soil of Fountains Valley itself with its humus, 25%."

"During the whole investigation, it only once occurred that highest transpiration coincided with the lowest relative moisture and highest temperature, although at times the maxima are near the time of the highest temperature in the afternoon. It may be safely concluded that in a semi-arid climate, on porous soil like shale, the transpiration of trees never follows temperature over a certain range, is not proportional to the increasing light, and certainly does not follow the decreasing relative moisture. On the contrary, the maxima are found not at the time of the strongest light, but earlier or later. Some of the maxima are even found at the time of the highest air moisture. One may ask whether transpiration only follows light, temperature and air moisture to a certain degree as, of course, there is no questioning the fact that light and temperature greatly increase the water output. For instance, the transition from night to day, the change in the evening from day to darkness, and even from sunlight to diffuse light, brings out the greatest changes in the water output.

"It is quite possible that light, especially when added to a high temperature, becomes too much for the trees, and that they therefore restrict their water output about noon. The sudden drop in transpiration when the light gets weaker towards 5 p.m., shows how much these

trees are affected by light, and not so much by temperature in the range of the investigation. The result is the graph with the decrease over the noon period."

"The author is convinced that the decreased transpiration about noon was partly due to an incipient drying or at least a water deficit (Maximov, 1929; Stocker, 1929) at that time, though no direct determination could be made during the veld experiment. Later in the afternoon the water intake apparently compensates for the loss of water by transpiration. The behaviour of the stomata is in close accordance with Stalfelt's findings (1929) that even in good light stomata close when water reserves are sinking. Even when external factors and the apertures of stomata are made responsible for the rate of transpiration, there must still be some internal factor of the plant which regulates it, otherwise, there would not be found, as in many of the investigated trees with fully open stomata, a very small transpiration at 5 p.m. on bright days."

"It is clear that our natural forest in the surroundings of Pretoria transpires well within the rainfall. Plenty of water is available for the undergrowth which considerably decreases the run-off of the water. As regards the exotics it is in most cases not the transpiration as such which preclude plantations; the espacement and size of the trees will be the deciding factor.

"If a plantation is not thinned out in time, a point may be reached when, even for conifers, there is not enough water in the soil to supply all the trees, and some of them must consequently die. This is what happened in plantations in the eastern Transvaal...where in 1933 about half the trees died. The espacement before the disaster was only three to four feet; after the dying off of the trees it was six to eight feet. The surviving trees withstood a further drought in 1937 perfectly well."

29. RELATIVE TRANSPIRATION OF CONIFEROUS AND BROAD-LEAVED TREES IN AUTUMN AND WINTER

J. E. Weaver and A. Mogensen. Bot. Gaz. 68(6): 393-424. 1919. (Reprinted by permission.)

At the University of Nebraska, transpiration of ponderosa pine, jack pine, lodgepole pine, white fir, Douglas-fir, white elm, bur oak, and soft maple seedlings was measured. Seedlings were grown in pots placed

outdoors. Pots were weighed daily and water added. Comparisons were mainly on a relative basis.

The seedlings with greatest leaf area had the highest water losses. Relative high transpiration rates in autumn were followed by a rapid reduction to very low winter rates. For ponderosa pine, for instance, "the entire period from Sept. 24 to Oct. 16 is characterized by relatively high transpiration losses after which there is a decided falling off. On Oct. 11 the stomata were found to be closed. The midwinter transpiration rates are exceedingly small. . . . A general but slow rise during the cold month of April may be noted, with a sharp increase following the milder weather in May." This general trend held for both conifers and hardwoods.

Summary:

"1. Autumn transpiration losses from conifers are just as great as or even greater than those from broad-leaves.

"2. The decrease in water losses from broad-leaved trees resulting from defoliation is gradual, and not greatly unlike the decrease shown in the transpiring power of conifers.

"3. Winter transpiration losses from conifers are only 1/55 - 1/251 as great as those in autumn.

"4. The increased losses of broad-leaved trees in spring occasioned by foliation are in proportion to the leaf areas exposed, and are closely controlled by weather conditions, but in the main are similar to increased losses of conifers.

"5. Winter transpiration losses from conifers are scarcely greater than those from defoliated stems of broad-leaved trees."

30. TRANSPIRATION RATES OF SOME FOREST TREE SPECIES DURING THE DORMANT SEASON

Theodore T. Kozlowski. Plant Physiol. 18: 252-260. 1943. (Reprinted by permission.)

Kozlowski compared the winter transpiration rates of white oak, yellow-poplar, sugar maple, cherry laurel, eastern white pine, and

loblolly pine. Three-year old seedlings were grown in buckets of sandy loam. Soil moisture was at field capacity at the beginning of the record, and water losses were replaced at the end of the experimental periods.

"...No great difference was observed in foliar transpiration of conifers and stem transpiration of deciduous species on a unit area basis [of leaf surface or stem area].

"The October-November average rate for loblolly pine and cherry laurel was more than twice the average maximum for December and January for white pine the October-November average rate was more than three times the December-January maximum.

"Independent comparisons of the evergreen versus deciduous species and of pines versus cherry laurel indicated highly significant differences on a unit area basis. During December and January the weekly transpiration rates of cherry laurel were approximately from 2 to 4 times as great as those of either of the pines. Comparisons of rates of loblolly pine versus eastern white pine, white oak versus yellow poplar and sugar maple, and yellow poplar versus sugar maple indicated no real statistical differences in transpiration of these species during the dormant season.

"A decrease in soil temperature was found to decrease the transpiration rates of loblolly pine and eastern white pine. This is in general agreement with results obtained by other investigations with herbaceous materials Transpiration of loblolly pine was reduced more than that of eastern white pine over the temperature range between 17° and 0° C. The difference in behavior of the two species is probably caused by differences in inherent protoplasmic qualities. The greater reduction in absorption by loblolly pine in cold soil might be a factor in its inability to survive in colder regions."

31. SOIL WATER IN RELATION TO TRANSPIRATION

V. M. Spalding. Torreya 5(2): 25-27. 1905.
(Reprinted by permission.)

"In a recent article by the writer on the creosote bush in its relation to water supply, the statement was made that the amount transpired appears to stand in direct relation to the amount of water available in the soil in which the plant is growing. Further observations on this and some other desert plants not only confirm this view but go to show that water in

the soil is a controlling factor, and that even as efficient an agent as light may, in comparison, take quite secondary rank."

"The plants employed were seedlings of the creosote bush (Covillea) and palo verde (Parkinsonia Torreyana and P. aculeata) growing in cans and supplied with measured quantities of water at stated intervals. The rate of transpiration was determined by placing the plants under a bell-jar, with suitable precautions to prevent the absorption or escape of water vapor, the amount of water transpired being derived from readings of a hygrometer."

"Beginning with the palo verde, two sets of plants, one serving as a check on the other, were used. August 11, the plants having been well watered the day before, the rate of transpiration was determined. The following day, August 12, the plants meantime having received no water, but having been treated precisely as before, as regards light and other controllable conditions, the rate of transpiration was found to be only 52.6 and 38.5 per cent, as high as it was on the preceding day, a result apparently attributable to nothing else than the diminished quantity of water in the soil in which the plants were growing."

"The same plants were again placed under observation August 18, having been given no water since August 15. External conditions were favorable to transpiration, full sunlight, a fresh breeze, and rather high temperature. At 11:40 A. M., after the rate of transpiration had been noted, number 1 was given one ounce, and number 2 three ounces of water. At 1:15 P. M., the rate of transpiration of number 1 was found to be the same as at the time of the preceding observation, while that of number 2 was twice as great. At 4:00 P. M., observations were again made, and at this second afternoon reading it was found that number 1 was transpiring twice and number 2 four times as rapidly as at the time of the forenoon observation."

"Experiments with Covillea gave even more striking results. September 5, the transpiration of two plants, designated 1 and 2, was determined in the forenoon between 11 and 12, and again in the afternoon between 3 and 4 o'clock. Number 2 was given three ounces of water at 12:20, none being given to number 1. At the time of the afternoon observation it was found that number 2 was transpiring more than three times as rapidly as it was before the water was given to it, and number 1, which was not watered, was transpiring only one-fifth as rapidly as it was in the forenoon."

"It was found that exposure to bright sunlight was uniformly followed by accelerated transpiration, whenever the plant under observation had a full supply of water, but that otherwise such acceleration did not take place."

"It is noteworthy that plants which had all along received a meagre supply of water were nevertheless in a position to transpire rapidly when once a full supply of water was furnished them, while plants which from the beginning had received a very large amount of water showed promptly a marked lowering in rate of transpiration when the water supply was reduced."

"With so complicated a problem general statements may well be made with extreme caution, but the evidence in the present case is sufficient to show that in studies of transpiration it is altogether unsafe to attempt to estimate any other factors whatever without taking due account of water in the soil."

32. INFLUENCE OF SOIL MOISTURE CONDITIONS ON APPARENT PHOTOSYNTHESIS AND TRANSPIRATION OF PECAN LEAVES

A. J. Loustalot. Jour. Agr. Res. 71(12): 519-532. 1945.

Loustalot grew seedlings in crocks of coarse sand and silt loam, and measured photosynthesis and transpiration as soil dried. The sand had a field capacity of 6 percent and a wilting coefficient of 1 percent; silt loam 34 and 12.2 percent respectively. During drying from July 18 to the morning of July 22, the soil moisture of sand dropped from about field capacity to 1.5 percent above the wilting point. The transpiration rate dropped to two-thirds of normal, but photosynthesis was not appreciably affected. During the afternoon of July 22 the rate of transpiration dropped sharply and photosynthesis was only two-thirds of normal.

Silt loam drying started September 7. By September 16, with soil moisture at 18 percent, there were small decreases in both photosynthesis and transpiration. By September 21, with soil moisture close to wilting point, transpiration dropped to one-half normal, photosynthesis to one-fifth normal.

"The amounts of reduction in the rates of photosynthesis and transpiration of leaves of pecan seedlings subjected to drought were

closely correlated with the proximity of the soil moisture to the wilting point as well as with the atmospheric conditions during the critical periods of moisture shortage. Under conditions highly favorable for moisture evaporation, as in the afternoons, photosynthesis almost ceased when the soil moisture was at the wilting point or slightly below; but the reduction in transpiration was considerably less. Under conditions less favorable for evaporation, as in the mornings, the transpiration rates were reduced to a greater extent relative to the reduction in the rates of photosynthesis, although the actual reduction in transpiration was usually somewhat less than that under conditions highly favorable for evaporation.

"The rate of recovery in photosynthesis and transpiration activity from the effects of drought was usually very rapid during the first day or two after termination of the drought, but several days more were required before the rates reached normal or their maximum."

33. INFLUENCE OF SOIL MOISTURE ON PHOTOSYNTHESIS, RESPIRATION, AND TRANSPIRATION OF APPLE LEAVES

G. William Schneider and N. F. Childers. Plant Physiol. 16: 565-583. 1941. (Reprinted by permission.)

"The results presented in this paper trace the daily effect of a gradually drying soil on apparent photosynthesis, respiration, and transpiration of small apple trees as the soil in which they were growing gradually dried to approximately the wilting percentage. . . . "

"Before wilting was evident, there were marked reductions in apparent photosynthesis and transpiration and an increase in respiration; in one case there was a 55 per cent reduction in photosynthesis, a 65 per cent reduction in transpiration, and a 62 per cent increase in respiration. Stomata at this time appeared to be completely closed."

"When water was applied to the soil in which wilted apple trees were growing, the leaves usually attained turgidity within three to five hours, depending upon their degree of wilting. They did not, however, recover to their original relationships with the controls in photosynthesis and respiration before two to seven days after the watering. Transpiration usually recovered about the same time as photosynthesis or slightly earlier."

34. CLIMATE AND SOIL MOISTURE

C. W. Thornthwaite. Unpublished manuscript. Undated. (By permission.)

"In 1894, a Division of Agricultural Soils was created in the Weather Bureau with Milton Whitney as Chief. This Division was expected to continue 'the study of rainfall and temperature after they enter the soil, and to keep a continuous record of the moisture and temperature conditions within some of the most important types of soil in the country.' " (Whitney, 1894).

The author cites data indicating that "...There is little difference in the proportionate amounts of water obtained by different types of plants from different depths of the soil. The percentage of water obtained from various depths of the soil is comparable to the percentage of feeding roots at different depths and depends upon the type of soil rather than the kind of vegetation."

"Investigations should be undertaken to determine the actual amount of water readily available to different types of vegetation growing in different soils. The few data that relate to the problem indicate that the frequency distribution of available moisture will range from about 2 inches to the neighborhood of 6 or 7 inches, with the most frequent value approximately 4 inches. These values may need to be revised upward or downward as additional observations are made. Nevertheless, it is to be expected that the amount of water available to plants in agricultural soils will prove to be far less variable than conventional studies of soil moisture would indicate.

"It has already been emphasized that plants are not absolutely limited to the equivalent of 4 inches of moisture in the soil. Their roots will grow into moist soil and get additional moisture. Such moisture enters the plant too slowly to aid effectively in satisfying its needs and transpiration is very small. The plant wilts daily and soon enters the stage of permanent wilting. Growth is retarded or stopped. It is often overlooked that root growth also stops, when food production stops in the green aerial parts. Thus, the more a plant may be in need of water, the less able it is to extend roots to get it.

"It is well known that plants can utilize the soil moisture from considerable depth in the event of a moisture deficiency in the surface layers. What is not generally appreciated is that this water utilization is at a much slower rate than the optimum. Life may be preserved in

the plant but its development is seriously arrested or even stopped. Miller (1938) states that transpiration under these conditions may be only one-twentieth to one-thirtieth of that which prevails when the optimum amount of moisture is present."

"When there is no deficiency of moisture in the soil and the roots are able to absorb the moisture freely, the rate and amount of transpiration are governed by atmospheric factors alone. This would represent the optimum water loss for the vegetation growing in the particular locality and may be designated the potential transpiration. If, on the other hand, soil moisture is deficient, the importance of the condition of the atmosphere diminishes and that of soil moisture supply increases. The actual transpiration is influenced by the moisture concentration in the soil as well as by atmospheric factors. Under natural conditions it is almost everywhere less than potential transpiration."

35. SOIL MOISTURE AND EVAPORATION

R. K. Schofield. Internatl. Cong. Soil Sci. Trans. 4(2): 20-28. 1950.

"...Regarding their transpiration plants are largely at the mercy of their physical environment. This important fact was for many years obscured by the use of the term 'transpiration ratio' to denote the ratio of the water transpired by a plant to the amount of dry matter produced by photosynthesis. There is, in fact, no quantitative relationship between transpiration and the production of dry matter. This is very clearly shown by the results of recent experiments conducted by Penman [1948] at Rothamsted in which measurements were made of the evaporation from several patches of short-cut grass. One of these received a heavy dressing of fertilizer and yielded three times more dry weight of grass cuttings than two others of equal size which did not receive fertilizers. The evaporation from (and hence the transpiration of) the fertilized grass was, however, no greater than that of the unfertilized."

"The principal reason for the seasonal variation of f [factor relating maximum evaporation (transpiration) from grass to evaporation from open water] appears to be the closing at night of the stomata of the leaves which interrupts transpiration.

Months in lat. 52°	Mean duration of daylight hours	Mean factor
Nov. to Feb. incl.	9.5	0.6
Mar. and Apr. Sept and Oct.	13	0.7
May to Aug. incl.	16.5	0.8

"...Up to a certain value, C, of the soil moisture deficit, evaporation goes on at the maximum rate. If after this deficit has been built up, evaporation continues to exceed rainfall it will fall more and more behind the maximum evaporation as the deficit increases."

" 'C' of course depends on the root habits of the plants as well as on the physical properties of the soil. If the depth of rooting can be increased C will be increased, and full crop growth will continue proportionately longer in a dry season. Here is yet another desirable property for which it may be possible to select and breed plants. Soil cultivation and manurial treatments appear more likely to increase C by increasing root penetration than by increasing the water-holding power of the soil."

36. THE ROLE OF VEGETATION IN METEOROLOGY, SOIL MECHANICS AND HYDROLOGY

H. L. Penman. Brit. Jour. Appl. Phys. 2:145-151. 1951.

"The important effects of plant transpiration are found where deficits can be built up. As the deficit increases the soil reaches a state of dryness at which extraction of water by the plant ceases to be easy, the transition being sharp in some soils gradual in others, i.e. there is a value of the deficit beyond which the transpiration rate no longer is as great as the potential rate calculable from weather data."

"The calculation of soil moisture deficit from weather data is only valid when there is adequate water available to meet the potential demand...The normal condition in large areas of the world...is that summer water supply is not sufficient to maintain maximum transpiration and growth. The plant's first main response to water shortage is to extend its root system, so tapping a deeper layer of soil, but there

are limits to the rate and extent of the growth and a stage is reached at which the plant must be satisfied with what it can draw from the soil remote from the roots, and because water movement in a drying soil is so very, very slow the transpiration rate falls off very abruptly to about one-tenth of what it could be."

E V A P O - T R A N S P I R A T I O N

37. EVAPORATION IN NATURE

E. L. Stone, Jr. Jour. Forestry 50(10): 746-747. 1952. (Reprinted by permission.)

"...It seems proper to call attention to the very pertinent work of the Rothamsted investigators, H. L. Penman and R. K. Schofield. Although not unknown in this country, this work is yet to have the impact which it surely must upon the thinking of all concerned with 'evaporation in nature'. Much of its significance lies in the very simple basic views of evapo-transpiration from land surfaces that emerge, together with a fresh approach to estimation of its magnitude."

"Penman and Schofield approached the problem of evaporation of water from any surface, including plant tissue, as a physical process accountable in terms of an energy balance. It was at once obvious that the only significant source of energy is direct solar radiation; in the case of a free water surface, evaporation accounts for some 40 percent of the total radiation received. Accordingly the annual variation in evaporation follows the solar radiation cycle closely and such correlation with mean periodic air temperature as may occur is due to their dependence on a common cause. Thus an analysis of some Rothamsted records showed little correlation between mean daily temperature and daily evaporation although the monthly means were correlated. Annual evaporation losses vary with latitude, approximating 15 inches from a free water surface in Ontario and 60 inches in the tropics.

"Since water absorbs very nearly all of the high energy radiation falling upon it, losses from a water surface represent the maximum possible values for natural evaporation. Measured losses from sod adequately supplied with moisture were approximately 80 percent of those from free water during the May-August period, with the lesser amount attributable in part to a greater reflectance of incoming radiation by the leaf surfaces. From other evidence it appeared likely that, so long as soil moisture was not limiting, deciduous forest and sod differed very little in the amount of water transpired. Nor did a trebling of dry matter production, brought about by fertilization of certain sod areas, increase water losses.

"Some of the implications for forest conditions are evident: Where soil moisture is restricted, equivalent areas of deep soil supporting unlike species or vegetation types may differ markedly in water loss because of differences in rooting depth. When moisture is not limit-

ing, however, losses from the various areas will probably be of similar magnitude and close to a fixed maximum, with such differences as do occur associated with reflectance of short wave radiation. When so supplied, the important factor is simply the radiation absorbed per unit land area (less losses to conduction and back radiation) and once full coverage of the area is obtained considerations of total leaf surface and height become of minor importance. Likewise air temperature, wind movement, and atmospheric humidity, within the usual ranges occurring during the growing season, are of much less significance than radiation in bringing about the vapor pressure differences on which evaporation depends.

"The consequences of this work challenge a number of beliefs and textbook generalities, some of them already suspect or discarded by watershed investigators. Thus evaporation measured from isolated trees or portions thereof cannot be related, even theoretically, to losses from an <u>area</u> of forest vegetation nor can the results of conventional pot cultures. 'Transpiration ratios' are likewise meaningless. Definite limits are set on evapo-transpiration losses from any area and the alleged superiority of one species over another is unlikely except as attributable to season of growth or rooting depth and habit. The separation of evaporation and transpiration on vegetated areas becomes of doubtful utility inasmuch as they cannot proceed independently; for the same reason the significance of canopy interception during the growing season may prove less than has been imagined."

38. NATURAL EVAPORATION FROM OPEN WATER, BARE SOIL AND GRASS

H. L. Penman. Proc. Roy. Soc., A, 193: 120-145. 1948.

"Evaporation from bare soil involves complex soil factors as well as atmospheric conditions: transpiration studies add to these further important physical and biological features, for a plant's root system can draw on moisture throughout a considerable depth of soil, its aerial parts permit vapour transfer throughout a considerable thickness of air, and its photo-sensitive stomatal mechanism restricts this transfer, in general, to the hours of daylight. A complete survey of evaporation from bare soil and of transpiration from crops should take account of all relevant factors, but the present account will be largely restricted to consideration of the early stages that would arise after thorough wetting of the soil by rain or irrigation, when soil

type, crop type and root range are of little importance."

"Two theoretical approaches to evaporation from saturated surfaces are outlined, the first being on an aerodynamic basis in which evaporation is regarded as due to turbulent transport of vapour by a process of eddy diffusion, and the second being on an energy basis in which evaporation is regarded as one of the ways of degrading incoming radiation. Neither approach is new, but a combination is suggested that eliminates the parameter measured with most difficulty--surface temperature--and provides for the first time an opportunity to make theoretical estimates of evaporation rates from standard meteorological data, estimates that can be retrospective."

"...For the combined estimate there must be known, mean air temperature, mean dewpoint temperature, mean wind velocity; and mean daily duration of sunshine."

"The evaporation rate from continuously wet bare soil is 0.9 that from an open water surface exposed to the weather conditions in all seasons.

"The corresponding relative evaporation rate from turf with a plentiful water supply varies with season of the year. Provisional values...for southern England are:

Midwinter (November - February)	0.6
Spring and autumn (March - April Sept. - Oct.)	0.7
Midsummer (May - August)	0.8
Whole year	0.75"

For the bare soil the water table was 5 inches below surface, for turf 16 inches.

39. THE MAGNITUDE AND REGIONAL DISTRIBUTION OF WATER LOSSES INFLUENCED BY VEGETATION

Joseph Kittredge, Jr. Jour. Forestry 36(8): 775-778. 1938. (Reprinted by permission.)

Sources of data were isohyetal maps of rainfall and runoff; the author subtracted runoff from rainfall to obtain estimated water losses by forest regions. Annual water loss:

Eastern regions	Inches	Western regions	Inches
Longleaf-loblolly-slash pine	30-40	Pacific Douglas-fir	25-60
River bottom hardwoods and cypress	30-40	Redwood	25-55
Oak-pine	25-35	Sugar and ponderosa pine	15-40
Oak-chestnut-yellow poplar	20-30	Western larch-western white pine	15-20
Oak-hickory	20-30	Spruce-fir	10-20
Tall grass	20-30	Ponderosa pine	10-20
Birch-beech-maple-hemlock	15-20	Short grass	10-20
White-red-jack pine	15-20	Lodgepole pine	10-15
Spruce-fir	10-20	Pinon-juniper	5-15
		Chaparral	5-15
		Sagebrush	5-10
		Desert shrub	4-10

In the East, "the regions thus form a series in which the losses are at a maximum in the South, where the temperatures are highest and the growing season longest, and in which they decrease progressively toward a minimum in the North. In general the order of the losses of the different types follows the same sequence as that of the growth rate of well-stocked forest stands."

"...In the West the progression from South to North is seriously disturbed by the low precipitation which prevails over much of the region and strictly limits the losses... For the forest types this progression from higher to lower water losses is again the progression from more rapid to less rapid growth, whether the differences in growth are limited by altitude and temperature or by deficient moisture."

40. AGRICULTURAL HYDROLOGY AS EVALUATED BY MONOLITH LYSIMETERS

L. L. Harrold and F. R. Dreibelbis. 149 pp. U. S. Dept. Agr. Tech. Bul. 1050. 1951.

"This bulletin is in the nature of a progress report on the lysimeter investigations carried on at the North Appalachian Experimental Watershed near Coshocton, Ohio, to 1949.

"The hydrologic data were obtained from eleven monolith lysimeters, each 0.002 acre in area and 8 feet deep, three of which were weighed automatically. The features of the installations, some of which are unique, are described. Records of precipitation, runoff, and percolation are presented for each lysimeter. Weight records provided data for determination of condensation-absorption of moisture from the atmosphere, evapo-transpiration of soil moisture, and changes in storage of soil moisture.

"The amount of moisture condensed and absorbed from the atmosphere was fairly large, amounting to over 6 inches of water annually. Of the water added to the soil, precipitation accounted for 81 percent and condensation-absorption 19 percent. From 80 to 85 percent of the soil-moisture depletion was due to evapo-transpiration. Percolation accounted for the remainder. Different crops had strikingly different effects on seasonal evapo-transpiration rates. Wheat and meadow crops depleted soil moisture most rapidly in May and June. Corn used water at high rates in July and August. Cultivating the cornland had a noticeable effect on evapo-transpiration, and the effect of hay cutting was still more marked."

"As expected, the growing season had the greatest ET [evapotranspiration]. June and July were the months of highest water demand by plants. The 6-year average daily ET for June ranged from 0.179 to 0.203 inch, and the July range of ET values was not materially different. The variation between the 6-year average ET values for the three lysimeters, for the different months is small. Average ET values for all lysimeters, however, had a definite trend throughout the year similar to that for air temperature. Average ET for the warm months was from three to four times as much as that for the cooler months. This difference reached a ratio as high as six to one in some years."

"Water removal from soil pores was more rapid when the land was in good sod and wheat than when it was in poor sod or corn. Conse-

quently, poor sod and cornland were less capable of absorbing storm rainfall at this season [May]. In July and August, however, ET from cornland was very great, especially in 1949, and the rate of soil-moisture depletion was high."

"...Moisture on vegetation from the preceding night, whether from rain or dew, had no noticeable effect on evapo-transpiration. Evapo-transpiration was no greater from wet vegetation than from dry...When there was little or no dew, larger quantities of soil water were used in the ET process. In other words, the evapo-transpiration from vegetated land following nights of little or no dew was mostly transpiration. Furthermore, sizeable quantities of the ET from land moistened by CA [condensation-absorption] must have been evaporation. Dew fall, or absorption of water by the soil, or both, have, therefore, a soil-moisture conservation value."

"A study of the crop use of water by semimonthly periods shows that the rate of water consumption varies during the growing period. Depletion of soil-water supplies by corn, for example, was greatest in July. The usage exceeded the normal rainfall in both the first and second half of this month 9 out of 10 times."

"Wheat used water most heavily in late May and early June. Use exceeded normal rainfall from the middle of April through the first half of June. Wheat usually removed water from soil pores by evapo-transpiration faster than cornland prior to June 15. Water needs for wheat diminished after June 15. This is the ripening period. Following wheat harvest and the removal of straw, the new meadow of timothy, red clover, and alfalfa put on rapid growth. Water consumption increased somewhat in late July and early August.

"Water use by first-year meadow....Vegetation was mostly red clover, timothy grass, and small alfalfa plants. Water consumption was greatest in the first half of June. Hay cutting in the last half of June decreased the demand for water. The second cutting of hay early in August 1947 had no noticeable effect on the semimonthly ET-CA. The cutting of August 1943 was effective in reducing ET-CA water usage. Hay cutting may result in striking changes in daily evapo-transpiration and condensation absorption...."

"These data show that the net soil-moisture depletion (ET-CA) is fairly rapid on land with a good meadow crop... ranging from 0.16 to 0.38 inch per day for a vigorous and full-grown legume-grass meadow. The removal of most of this growth decreased the daily loss of soil moisture by at least one-half. The reduction may reach two-thirds, as in June 1947."

41. CONSUMPTIVE USE OF WATER. A SYMPOSIUM.
<u>Forest and range vegetation.</u>

L. R. Rich. Trans. Amer. Soc. Civ. Engin. 117: 974-987. 1952. (Reprinted by permission.)

"Data from studies at Sierra Ancha Experimental Forest [central Arizona] have shown small differences in consumptive use between areas kept bare of vegetation and areas in various types of vegetation, and no significant differences in consumptive use between a watershed with good and poor grass cover. Decreased use on bare watersheds is largely hypothetical since no watershed can be kept bare of all vegetation; some plants will grow under extremely adverse conditions. If perennial grasses are depleted through abuse, inferior species such as annuals, weeds, and half-shrubs usually replace the original vegetation. If chaparral species are burned out, the sprouting varieties readily recover and may even increase.

"From a water-yield standpoint, the major question is not whether watersheds bare of vegetation would yield most water, but the type of vegetation that interferes least with water yield and still controls sediment. In the Southwest, with very few exceptions, grasses are dormant and do not use water during the winter water-yielding period. Water use is largely confined to the summer period when there is no surplus water, and surface evaporation alone could consume all the precipitation. During the winter, high transpiration by half-shrubs, winter annuals, and evergreen shrubs, all characteristic of a deteriorated vegetation, tends to reduce water yield. Total annual use by grasses is slightly higher than evaporation from bare ground but lower than losses from a deteriorated vegetation. The benefit of well-developed and well-maintained plant cover in checking soil erosion and sedimentation of reservoirs outweighs by many times the value of the slight amount of water it uses.

"Consumptive use of water by forest and range vegetation depends primarily on climatic and watershed conditions and on water availability. There are few areas in the West where unlimited water is available for full potential consumptive use. The ability of plants to grow and use water is greatest in summer and least in winter. . . . Actual use is dependent on growing conditions when moisture is available. The availability of moisture depends on distribution of precipitation and the moisture held in the soil for use during drought periods. Water use in the semidesert grassland zone was 92% of the precipitation for perennial grasses, 98% for winter annuals, and 89% of the precipitation lost from bare soil by evaporation. Consumptive use of water in the chaparral zone was 81% of the precipitation for grasses, 84% of the precipitation for shrubs, and 78% of the precipitation lost from bare soil by evaporation. The use on watersheds in the mixed grassland-chaparral zone varied from 90% to 95% of the precipitation on 4 adjacent watersheds, depending on soil type and depth of soil. Water on forested watersheds has varied from 77% to 90% of the rainfall, depending on depth of soil and slope."

42. EFFECT OF REMOVAL OF FOREST VEGETATION UPON WATER-YIELDS

M. D. Hoover. Trans. Amer. Geophys. Union. Part VI: 969-975. 1944. (Reprinted by permission.)

"The location of the experimental watersheds is the Coweeta Experimental Forest, a field-laboratory of the [Southeastern] Forest Experiment Station. It is situated in the Nantahala Range of the southern Appalachian Mountains near Franklin, North Carolina. This region is in the zone of maximum precipitation in the eastern United States."

"Natural vegetation is composed of deciduous trees with abundant shrubs and minor vegetation. Because of the favorable climate plant-growth is rapid and but rarely checked by summer droughts.

"Under these conditions, vegetation has a maximum opportunity for transpiration. Soil-moisture seldom reaches the wilting-point and does not become a limiting factor for growth of established plants."

"The plan of this experiment was to compare water-yield for a watershed before and after removal of forest. Before cutting, sufficient stream-flow and climatic records were to be obtained so that the normal relationship between rainfall and runoff could be established. In addition, another similar drainage-area was to be left uncut to serve as a control."

"All woody vegetation on [the treated] watershed was cut between January 6 and March 31, 1941. To prevent disturbance to the soil, trees were left where they fell and no material was removed. Tops and limbs were lopped to lay close to the ground and scattered uniformly over the soil-surface. Because of the large proportion of evergreen rhododendron and mountainlaurel, the resulting slash-cover formed a loose mulch over the area. This protected the soil and maintained infiltration-capacity. It also served to protect the soil from drying by sun and wind, preventing any great increase in evaporation after cutting. An isolation strip 50 feet in width around the watershed-boundary received identical treatment."

"The cumulative runoff from April 1 to March 31 was 17.29 inches for 1941-42 and 13.26 inches for 1942-43. The value for the first year was obtained under minimum plant-cover and should approximate the transpiration that would have occurred under natural forest-cover. A lower value occurred in the second year because the sprouts had a longer average opportunity for growth."

"The maximum monthly increase to runoff of 2.84 inches occurred in July 1941. In this month rainfall was 10.80 inches but preceding rainfall was deficient. Under forested conditions the heavy rainfall in July was barely sufficient to satisfy soil-moisture deficiencies and but little runoff resulted. However, on the treated area, because of the lower drain on soil-moisture, the rains during July made large contributions to ground-water storage resulting in a greatly increased runoff for this and the following months. The normal period of soil-moisture replenishment is in the fall. In both 1941 and 1942 the rapid replenishment of soil-moisture on the treated area resulted in a large increase to runoff during this time."

43. DISPOSITION OF RAINFALL IN TWO MOUNTAIN AREAS OF CALIFORNIA

P. B. Rowe and E. A. Colman. 84 pp. U. S. Dept. Agr. Tech. Bul. 1048. 1951.

Evapo-transpiration losses were determined in woodland chaparral and ponderosa pine in central California, and under brush cover in southern California.

"A large part of the annual evapo-transpiration loss took place during the spring and summer dry season. The loss during this drying period ranged from 56 percent of the total annual loss in the woodland chaparral to 76 percent of the annual loss in the ponderosa pine. The water thus lost included all water stored in the soil from field capacity to slightly below wilting point and in addition all water added to the soil by the infrequent late spring and summer rains. Under the conditions of winter rain and summer drought typical of these areas the annual evapo-transpiration loss was more strongly influenced by the available water storage capacity of the soil than by any other factor."

"Water-loss rates decreased markedly at about the time when each soil layer reached wilting-point storage. This was true of all the vegetated plots studied. It seems probable, from this information, that the woody vegetation on these plots can draw little if any more water from the soil than can herbaceous plants, which are known to suffer from lack of water when soil moisture has been depleted to the wilting point. Yet the woody plants involved in this study do not die, even when exposed to soil having less than wilting-point storage for months at a time (nearly 3 1/2 months for 1940). During such periods the plants cannot obtain any significant quantity of water from the soil, nor is any appreciable amount available to them from the underlying rock. Therefore it must be assumed for the present that these plants survive the summer drought by entering some type of dormant state. This assumption is supported by the observation that chaparral shrubs grown in soil confined in lysimeters at San Dimas have survived even though the moisture content of the confined soil remained below the wilting point for as long as 5 months at a time."

"Removing the vegetation, trenching, and maintaining a bare surface on plots in the woodland chaparral, ponderosa pine, and San Dimas chaparral eliminated all interception and transpiration loss. Surface runoff and soil erosion were greatly increased but evaporative loss of water from the soil was reduced. As a result of the reduced evaporative losses there was a greater carryover of soil water on these plots from one year to the next than was found on the annually burned or natural plots. During each summer the bare soils lost appreciable quantities of water from all depths, but drying was much slower and less complete in the deeper soil layers. Thus the plots with deep soil entered each rainy season with a proportionately greater carryover of water than did those with shallow soil."

"...It appears that denudation is more effective in reducing evaporation losses from deep than from shallow soils, and from soils protected from full insolation than from those exposed to sun and wind."

"...Increases in usable water yield can possibly be achieved in this area if soils are deep, by reducing interception and evapo-transpiration losses, but only if surface runoff and soil erosion can be controlled."

44. ESTIMATING THE MOISTURE CONTENT OF THE 0- TO 6- INCH SOIL HORIZON FROM CLIMATIC DATA

A. W. Zingg. Soil Sci. Soc. Amer. Proc. 8: 109-111. 1944. (Reprinted by permission.)

"Measurements of soil moisture were secured under various crops during the 3-year period 1934-36 on the Shelby loam soil at the Soil Conservation Research Station at Bethany, Mo. During this period soil moisture determinations were made under crops of corn, small grain, meadow, and bluegrass on 62 occasions."

Average results of triplicate soil samples taken in the 0 - 6 inch horizon were used in this analysis.

"As an initial approach to the problem, triplicate field moisture determinations on a given date for each of the crops of corn, small grain and meadow were averaged. These crops represent a 3-year crop rotation commonly grown in the soils region and the average moisture figure on a given date would, therefore, represent rotation average moisture."

"Rotation moisture was correlated with various combinations of temperature and rainfall, and time of occurrence thereof. Lapse of time required for rainfall to accumulate to a total of 1/2 inch, and finally, a factor for estimating the moisture content at a prior date were added in an attempt to further refine such relationships. Data for the winter months were excluded to avoid snow and freezing temperature."

"After determining the relationship of factors resulting in the most practical equation for estimating moisture under the crop rotation, equations containing these identical variables were derived for moisture under individual crops."

Total precipitation in inches for 21 days prior to moisture determination and mean 21-day temperature in F ^{o} prior to moisture determination, and the number of days required for rainfall to total 1/2 inch prior to the time of moisture determination, gave the most practical equation for estimating soil moisture.

From graphs of actual and predicted moisture contents for the four crops: "Reasonable agreement between the two graphs is obtained and the ability of the estimating equations to show changes between crops, and high or low moisture content for all crops as a whole is illustrated. A seasonal trend in moisture, wherein moisture is lowest in July, is also apparent."

45. DETERMINING WATER REQUIREMENTS IN IRRIGATED AREAS FROM CLIMATOLOGICAL AND IRRIGATION DATA

Harry F. Blaney and Wayne D. Criddle. U. S. Dept. Agr. SCS-TP-96. 1950.

"Consumptive use (evapo-transpiration): The sum of the volumes of water used by the vegetative growth of a given area in transpiration and building of plant tissue and that evaporated from adjacent soil, snow or intercepted precipitation on the area in any specified time, divided by the given area."

The authors discuss factors that affect consumptive use: precipitation, temperature, humidity, wind movement, growing season, latitude, available irrigation water supply, soil fertility, and plant pests and diseases.

"...Consumptive use of water is affected by numerous independent and related variables; and of the climatic factors affecting plant growth, temperature and precipitation undoubtedly have the greatest influence. Furthermore, records of temperature and precipitation are far more universally available throughout the western States than are data for other factors. The actual hours of sunshine also play an important part in the rate at which plants grow and consume water, but sunshine records are not generally available. The theoretical daytime hours for each day are available for all the latitudes [Marvin, 1905] and may be used in place of the actual data. Although it is recognized that these may be misleading in areas where heavy fog or stormy weather exists during a large part of the year, temperatures tend to correct for

such a condition. Humidity records, if available, may also be used as a correction. [Blaney, Morin, and Criddle, 1942]

"Disregarding the unmeasured factors, consumptive use varies with the temperature, daytime hours, and available moisture (precipitation, irrigation water or natural ground water). By multiplying the mean monthly temperature (t) by the monthly percent of daytime hours of the year (p), there is obtained a monthly consumptive-use factor (f). It is assumed that the consumptive use varies directly as this factor when an ample water supply is available. Expressed mathematically, $U = KF = \text{sum of } kf$ where

U = Consumptive use of crop (or evapo-transpiration) in inches for any period.

F = Sum of monthly consumptive-use factors for the period (sum of the products of mean monthly temperature and monthly percent of daytime hours of the year).

K = Empirical consumptive-use coefficient (irrigation season or growing period).

t = Mean monthly temperature, in degrees Fahrenheit.

p = Monthly percent of daytime hours of the year.

$f = \dfrac{t \times p}{100}$ = monthly consumptive use factor.

k = Monthly consumptive-use coefficient.

u = kf = monthly consumptive use in inches."

"The consumptive use factor (F) for any period may be computed for areas for which monthly temperature records are available. Then by knowing the consumptive-use coefficient (K) for a particular crop in some locality, an estimate of the use by the same crop in some other area may be made by application of the formula $U = KF$."

The authors calculated K from $K = \dfrac{U}{F}$, having obtained values of U from previous investigations. K varies somewhat because of different conditions (soils, water supply and method) in various studies. For normal conditions it is as follows:

Crop	Length of growing season or period	Consumptive-use coefficient 1/ (K)
Alfalfa	Between frosts	0.80 to 0.85
Beans	3 months	.60 to .70
Corn	4 months	.75 to .85
Cotton	7 months	.60 to .65
Flax	7 to 8 months	.80
Grains, small	3 months	.75 to .85
Grains, sorghums	4 to 5 months	.70
Orchard, citrus	7 months	.50 to .65
Orchard, walnuts	Between frosts	.70
Orchard, deciduous	Between frosts	.60 to .70
Pasture, grass	Between frosts	.75
Pasture, Ladino clover	Between frosts	.80 to .85
Potatoes	3 1/2 months	.65 to .75
Rice	3 to 5 months	1.00 to 1.20
Sugar beets	6 months	.65 to .75
Tomatoes	4 months	.70
Truck - small	3 months	.60

1/ The lower values of K are for coastal areas, the higher values for areas with an arid climate.

"The coefficients so developed are used to transpose the consumptive-use data for a given area to other areas for which only climatological data are available. The net amount of irrigation water necessary to satisfy consumptive use is found by subtracting the effective precipitation from the consumptive water requirement during the growing or irrigation season. This net requirement, divided by the irrigation efficiency, indicates the seasonal irrigation requirement of the crop."

46. AN APPROACH TOWARD A RATIONAL CLASSIFICATION OF CLIMATE

C. W. Thornthwaite. Geog. Rev. 38(1): 55-94. 1948. (Reprinted by permission.)

"We cannot tell whether a climate is moist or dry by knowing the precipitation alone. We must know whether precipitation is greater

or less than the water needed for evaporation and transpiration. Precipitation and evapotranspiration are equally important climatic factors."

"The vegetation of the desert is sparse and uses little water because water is deficient. If more water were available, the vegetation would be less sparse and would use more water. There is a distinction, then, between the amount of water that actually transpires and evaporates and that which would transpire and evaporate if it were available. When water supply increases, as in a desert irrigation project, evapotranspiration rises to a maximum that depends only on the climate. This we may call 'potential evapotranspiration', as distinct from 'actual evapotranspiration'.

"We know very little about either actual evapotranspiration or potential evapotranspiration. We shall be able to measure actual evapotranspiration as soon as existing methods are perfected. But to determine potential evapotranspiration is very difficult. Since it does not represent actual transfer of water to the atmosphere but rather the transfer that would be possible under ideal conditions of soil moisture and vegetation, it usually cannot be measured directly but must be determined experimentally. Like actual evapotranspiration, potential evapotranspiration is clearly a climatic element of great importance. By comparing it with precipitation we can obtain a rational definition of the moisture factor."

"Although the various methods of determining potential evapotranspiration have many faults and the determinations are scattered and few, we get from them an idea of how much water is transpired and evaporated and how much would be if it were available. We find that the rate of evapotranspiration depends on four things; climate, soil-moisture supply, plant cover, and land management. Of these the first two prove to be by far the most important.

"Some scientists have believed that transpiration serves no useful purpose for the plant. We now understand that transpiration effectively prevents the plant surfaces that are exposed to sunlight from being overheated. Most plants require sunlight for growth. The energy of the sun combines water and carbon dioxide in the leaves into food, which is later carried to all parts of the plant and used in growth. This process, which is called 'photo-synthesis', is most efficient when the leaf temperatures are between 85° and 90° F. But a leaf exposed to direct sunlight would quickly become much hotter if the energy of the sun were not disposed of in some way. The surface of dry ground may

reach a temperature of 200° F.; temperatures higher than 160° F. have been measured one-fourth of an inch below the ground surface. The plant is admirably designed to dissipate heat, the leaves being like the fins of a radiator, and some of the excess heat is conducted into the adjacent air and carried away in turbulence bodies. In this way the air is heated. But some of the excess heat energy is utilized in transpiration, to change water from a liquid into a vapor. Most of the heat of evaporation must come from the plant. Thus, the greater the intensity of sunshine, the greater will be the tendency to overheating, and the larger will be the transpiration of a plant exposed to it, if water is available for the process. Transpiration is a heat regulator, preventing temperature excesses in both plant and air. Dew formation at night is the reverse of this process and tends to prevent low temperature extremes, since the heat released goes mainly to the plant. Both transpiration and growth are related to temperature in the same way.

"Atmospheric elements whose influence on transpiration has been studied include solar radiation, air temperature, wind, and atmospheric humidity. These factors are all interrelated. Although solar radiation is the basic factor, there seems to be a closer parallelism between air temperature and transpiration. The temperature of the transpiring part is most closely related to the rate of transpiration.

"Transpiration and growth are both affected in the same way by variations in soil moisture. Both increase with increase of available water in the root zone of the soil, to an optimum. Above the optimum both are less, presumably because of poor aeration of the soil, which results in a lack of oxygen to supply the roots and an excess of carbon dioxide [Loustalot, 1945; Schneider and Childers, 1941]. On the other hand, as water in the soil increases above the optimum for growth, direct evaporation from the soil surface also continues to increase.

"We do not yet know how much we may increase or decrease transpiration by varying the type of plants or by modifying the plant cover. Since transpiration regulates leaf temperature, and since most plants reach their optimum growth at about the same temperature, we probably cannot change it very much except by reducing the density of the plant cover and thus wasting a part of the solar energy. If all the vegetation is removed from a field, there will be no transpiration. But as long as the root zone of the soil is well supplied with water, the amount of water transpired from a completely covered area will depend more on the amount of solar energy received by the surface and the resultant temperature than on the kind of plants."

"...Determinations have shown that potential evapotranspiration is high in the southern part of the United States and low in the northern part and that it varies greatly from winter to summer. From observations...it has been found that when adjustments are made for variation in day length, there is a close relation between mean monthly temperature and potential evapotranspiration. Study of all available data has resulted in a formula that permits the computation of potential evapotranspiration of a place if its latitude is known and if temperature records are available. The formula is given, and its use described...."

47. MANUAL OF EVAPOTRANSPIRATION

John R. Mather. The Johns Hopkins University Laboratory of Climatology, Micrometeorology of the Surface Layer of the Atmosphere. Supplement to Interim Report No. 10. April 1, 1950, to June 30, 1950. (Reprinted by permission.)

"Values of evapotranspiration may be obtained for short periods of time with the use of empirical formulae. It has long been realized that a number of meteorological factors are important in determining the amount of evapotranspiration that will occur. These factors include the temperature of the soil which in turn depends on the insolation and air temperature; in addition, evapotranspiration depends on the dew point temperature of the air, the wind velocity, and the roughness of the ground. Although many attempts have been made to find a relation between evapotranspiration and one or more of these factors, no definite relationship has emerged. The reason for this is that the amount of evapotranspiration depends also on the amount of moisture in the soil available to be utilized. Thus during drought conditions, evapotranspiration will be far different than during moist conditions. Although various expressions have been worked out relating evapotranspiration to meteorologic factors and the number of days since the last rain no good relationship has been found.

"In an effort to obtain a clearer understanding of evapotranspiration, Thornthwaite (1948) suggested the concept of potential evapotranspiration. Potential evapotranspiration is defined as the amount of water which will be lost from a surface completely covered with vegetation if there is sufficient water in the soil at all times for the use of the vegetation. Adequate moisture can be insured if the soil moisture tension is always maintained below 100 mb. The moisture in the soil would then be above the field capacity.

"Potential evapotranspiration offers an approach toward the understanding of the role of moisture in climate. The climatic elements that are usually measured -- temperature, precipitation, humidity, pressure, and wind -- do not by themselves equal climate. Evaporation or evapotranspiration, which is the transfer of moisture from the soil and plants to the atmosphere, is as much an element of climate as is precipitation, yet it is seldom included in the measurements of climatic stations. Because instruments are available to give us measurements of precipitation easily, we know its distribution over the earth through time reasonably well. The lack of adequate instruments or techniques to measure the movement of water from the earth to the atmosphere has sorely hampered our knowledge of the evaporation phase of climate.

"It is recognized that precipitation by itself does not indicate whether a climate is moist or dry. Only the relation between the water need of a place and the amount of precipitation will indicate this. Thus the yearly distribution of evapotranspiration is a climatic factor as important as precipitation. Actual evapotranspiration, as has been shown, depends, among other things, on the amount of water available in the soil. During drought periods evapotranspiration will practically cease so that it is difficult to obtain a picture of true water-need."

"With the further use of evapotranspirometers several problems demand immediate solution. It was stated before that potential evapotranspiration depends on climate, soil moisture supply, plant cover, and land management. In order to evaluate its dependence on the climatic factors its relation to the other three factors should be investigated. Work already in progress indicates that potential evapotranspiration is independent of land management practices and kind of crop cover within a wide range of economic crops. As long as the soil moisture tension is less than 100 mb., potential evapotranspiration is also independent of soil type or structure. Some dependence on the density and stage of growth of the crop has been found."

48. REPORT OF THE COMMITTEE ON TRANSPIRATION AND EVAPORATION, 1943 --1944

Contribution by C. W. Thornthwaite. Trans. Amer. Geophys. Union Part V: 686-693. 1945. (Reprinted by permission.)

Presents an equation for calculating potential evapo-transpiration and shows close correspondence between predicted and actual runoff.

"There are still many unanswered questions in my mind, but space here does not permit me to state them. An implied conclusion of this study is that evapotranspiration is independent of the character of the plant-cover, of soil-type, and of land-utilization to the extent that it varies under ordinary conditions. This conclusion is contrary to currently accepted notions concerning evapotranspiration-losses and I am reluctant to accept it myself; however, I have not yet found a reason for denying it. Of course, it is clear that the evapotranspiration regime can be altered. Destruction of vegetation will eliminate transpiration and mulching of bare soil will greatly reduce evaporation. But such practices are not carried out on a wide scale and surely could not modify the evapotranspiration map of the United States."

49. EVAPOTRANSPIRATION ESTIMATES AS CRITERIA FOR DETERMINING TIME OF IRRIGATION

E. H. M. van Bavel and T. V. Wilson. Agr. Eng. 33(7): 417-418, 420. 1952. (Reprinted by permission.)

"On drained land, water is lost by evaporation from the land surface and by transpiration of the vegetative cover. The combined process, known as evapotranspiration, accounts for all water losses while irrigation and rainfall minus runoff account for all additions. It follows that, if the quantities of water added to the soil were known and if the total daily evapotranspiration amounts were known, a simple bank account procedure could be used to determine the readily available supply of water in the soil at any time. When this supply appears to be reduced to zero, or nearly so, the need for irrigation is indicated."

"The use of the outlined principle entails two main sources of error. In the first place, it is not always easy to determine what proportion of rainfall infiltrates to replenish soil moisture, particularly in the case of high-intensity rainstorms. Fortunately, in the case of heavy rains exceeding the available water-storage capacity of the soil, runoff is oftentimes not too significant because it would represent surplus water, whether it entered the soil or not. However, there are some summer rains that fall at high intensities for short duration which, even on dry soils, exceed the maximum infiltration rate.

"Secondly, one must have a reasonably accurate estimate of evapotranspiration losses. Considering the fact that such losses are determined by such variable factors as the radiant energy from the

sun, the wind velocity, the temperature of the air, the relative humidity of the air, the temperature of the leaf or ground surface, and the density of cover, it seems that computing evapotranspiration might be a complicated process, the results of which have small general value. Actually, experience has shown, as will be discussed later, that evapotranspiration values computed from long-time averages of the cited meteorological factors have considerable validity. This is possibly due to the fact that the daily variations, if considered over several days, very nearly cancel each other. It must also be remembered that the estimate of evapotranspiration need not be any more accurate than the other elements of the computation, such as the rainfall record, error due to runoff, and variable soil moisture characteristics."

"An important question is, whether the evapotranspiration of different crops is different under similar conditions. So far, provided an ample moisture supply is in the soil, few experimental data would support this view. More research should be done to explore this point. The work reported here is based on the assumption that a closed vegetative cover under equal meteorological conditions disposes of the soil water supply with equal rapidity, regardless of botanical composition.

"The practical application can probably best be brought out by an example here arbitrarily taken to be a field of tobacco on Ruston coarse sandy loam at Raleigh, N. C., in July. The moisture characteristic of a Ruston coarse sandy loam shows that at field capacity (occurring at 50 cm. tension) the moisture content is 12.5 percent. If the maximum allowable tension is taken at 800 cm. of water (unpublished data indicate this value, but its exact magnitude is not important for this discussion) the corresponding moisture content is 4.4 percent. The maximum useful capacity is then 8.1 percent and for a rooting depth of 12 in. and a bulk density of 1.55, this represents 1.50 in. of water.

"According to Thornthwaite, the daily evapotranspiration for the Raleigh area is 0.21 in. in July. Therefore, as indicated in Table 1, by subtracting evapotranspiration from the supply and by adding rainfall and irrigation to the supply, a running record of available soil moisture can be kept.

Table 1. Example of a Soil Moisture Account
Ruston coarse sandy loam

Volume weight, 1.55
Moisture content (weight basis) at field capacity = 12.5 per cent
Moisture content at maximum allowable tension = 4.4 per cent
Useful moisture range 8.1 per cent

Volume of water in useful range (12 in. of soil) 1.50 in.

Date	Evapotranspiration	Precipitation	Irrigation	Supply
July 1	0.21	1.80		1.50
2	0.21			1.29
3	0.21			1.08
4	0.21			0.87
5	0.21	0.26		0.92
6	0.21			0.71
7	0.21			0.50
8	0.21			0.29
9	0.21			0.08
10	0.21		1.50	1.37
11	0.21			1.16
12	0.21	1.06		1.50

"When a need for irrigation is indicated as on July 10 in Table 1, 1.50 in. should be applied. Rainfall is also added to the supply, except when the total exceeds 1.5 in. If 1.5 in. is exceeded, the additional water is not added to the supply because it becomes unavailable to the plants by storage beyond the root zone or by drainage to the water table.

"In order to use the evapotranspiration approach, the rooting depth of the crop, the moisture characteristic of the soil, the moisture-tension tolerance of the crop, evapotranspiration rates, and a record of rainfall will have to be known."

ROOTS AND SOIL MOISTURE

50. RATE OF LEAF ELONGATION AS AFFECTED BY THE INTENSITY OF THE TOTAL SOIL MOISTURE STRESS

C. H. Wadleigh and H. C. Gauch. Plant Physiol. 23(4): 485-495. 1948. (Reprinted by permission.)

"It is difficult to evaluate the moisture stress to which a plant is responding when grown on a given mass of saline soil. This moisture stress which is conditioning the entry of water into the roots will be largely affected by five variables (a) the variation in salt distribution within the soil mass and its consequent effect on the variation in the osmotic pressure of the soil solution at a given moisture content; (b) variation in osmotic pressure in relation to change in moisture content; (c) variation in moisture tension in relation to moisture content; (d) variation in moisture content within the soil mass at a given time; and (e) variation in total water content of the soil mass with time, i.e., over an irrigation interval."

Rates of leaf elongation of cotton plants grown in steel drums containing 100 lbs. of loam were found to vary with moisture stress, a parabolic relation in which cessation of growth was mathematically calculated to occur consistently close to 15 atmospheres stress.

51. DISTRIBUTION OF SOIL MOISTURE UNDER ISOLATED FOREST TREES

H. A. Lunt. Jour. Agr. Res. 49(8): 695-703. 1934.

"...The whole root system is involved in moisture absorption and not any one particular portion. This is not true of nutrient absorption, since the bulk of the available plant nutrient supply, particularly nitrogen, is to be found comparatively close to the surface, and therefore most of the feeding roots are located in that portion of the profile. This is particularly true in northern forests where there is a considerable accumulation of duff on the forest floor. In other words, the tree may obtain most of its nutrients from the surface 10 or 12 inches, but except in wet soils it must draw also upon the subsoil to meet its moisture needs."

52. ROOT DEVELOPMENT AND SOIL MOISTURE

John P. Conrad and F. J. Veihmeyer. Hilgardia 4: 113-134. 1929. (Reprinted by permission.)

"...Moisture under rows of grain-sorghum plants is apparently extracted in successive zones and the extraction is progressive whenever no material additions of moisture occur during the growing season.

"The percentages for relative wetness expressed as ratios of soil-moisture contents to their respective moisture equivalents, may be used to indicate the development of roots, and the results of adequate moisture samples, taken at proper times, indicate with a fair degree of accuracy the presence or absence of roots of plants growing on the soil tested."

"A correlation has been shown to exist under conditions of this study between the amount of roots and the extent to which the soil has been dried by root activity. The writers reason that if the soil is wet at the beginning of the growing season to the full depth to which roots of plants would normally penetrate, subsequent addition of water by rain or irrigation, unless adverse conditions for growth are brought about thereby, can have but little influence on the extent of the root system developed."

53. RANGE OF SOIL-MOISTURE PERCENTAGES THROUGH WHICH PLANTS UNDERGO PERMANENT WILTING IN SOME SOILS FROM SEMIARID IRRIGATED AREAS

J. R. Furr and J. O. Reeve. Jour. Agr. Res. 71(4): 149-170. 1945.

"...The first permanent wilting point is marked by permanent wilting of the basal leaves [sunflower as test plant], and the lower end of the range, the ultimate wilting point, is marked by complete permanent wilting of the apical leaves."

"At soil-moisture percentages near or in the wilting range even a low rate of water loss from the plant had an appreciable effect upon the osmotic pressure of the sap and upon the turgor of the plant. A decrease in soil moisture from field capacity to the first permanent wilting point caused, in plants in dry air, an increase of 5 atmospheres in the osmotic pressure of the sap and, in plants in humid air, an increase of only 2.5

atmospheres. The changes in osmotic pressure of plants in humid air indicate that the diffusion-pressure deficit of the plant was somewhat less than 9 atmospheres at the first permanent wilting point and about 22 atmospheres at the ultimate wilting point."

"From extensive field work relating to irrigation problems, there has been formulated the following picture of the typical pattern of root distribution and the sequence of events in the extraction of water from soil initially wet to soil at the ultimate wilting point. While the distribution of roots varies greatly with species and soil, the concentration of absorbing roots is typically greatest in the upper part of the root zone and near the base of the plant and decreases with soil depth or distance from the plant. Extraction of water is most rapid in zones of highest root concentration and most favorable conditions of temperature, aeration, and other environmental factors. When the moisture content in the zone of highest root concentration has been reduced to the first permanent wilting point, extraction in this zone does not cease, but the rate falls off sharply and the total water absorption rate of the plant decreases. As the total absorption rate and the turgor of the plant decrease, the diffusion-pressure deficit of the root system as a whole increases, the soil-moisture percentage is lowered into the wilting range progressively in zones of lower and lower root concentration, and, finally, as the severity of wilting increases, the soil-moisture percentage is reduced to the ultimate wilting point progressively from zones of highest root concentration to zones of lower root concentration. By the time the plant in the field dies as a result of desiccation, the soil-moisture percentage in a large part of the root zone may have been reduced to the ultimate wilting point. Soil at the extremities of the root system, however, may still be well above the first permanent wilting point. The plant dies, not because water absorption has absolutely ceased, but because the rate of absorption finally lags too far behind the rate of loss to support life."

54. PEAR ROOT CONCENTRATION IN RELATION TO SOIL MOISTURE EXTRACTION IN HEAVY CLAY SOIL

W. W. Aldrich, R. A. Work, M. R. Lewis. Jour. Agr. Res. 50(12): 975-988. 1935.

In a pear orchard (trees 30 feet apart) in the Rouge River Valley of Oregon the authors took soil samples in one-foot increments with a King tube. They then determined the rate of soil-moisture extraction

during summer, when soil moisture decrease was rapid and unaffected by rainfall or irrigation for one or more periods. The amount of moisture extracted was expressed as a percentage of the sum of moisture decrease for all depths. The relative root concentration was expressed as a percentage of the sum of concentrations.

Depth (ft.)	Average extraction (percent)	Relative root concentration (percent)
0 - 1	34	36
1 - 2	28	31
2 - 3	22	22
3 - 4	16	11

r = 0.98 ± 0.01

55. A NEW TECHNIQUE FOR STUDYING THE ABSORPTION OF MOISTURE AND NUTRIENTS FROM SOIL BY PLANT ROOTS

Albert S. Hunter and Omer J. Kelley. Soil Sci. 62: 441-450. 1946. The Williams and Wilkins Co. (Reprinted by permission.)

"A new technique was developed for the study of the behavior of plant root systems in the absorption of moisture and nutrients from soil. Guayule and alfalfa plants were grown in columns of soil 72 inches tall, divided into 8-inch sections by means of tar-paraffin membranes which were permeable to roots but which restricted the movement of water and nutrients between adjoining sections. Each 8-inch section of the soil column was provided independently with a tensiometer and a Bouyoucos block, for the continuous measurement of soil moisture _in situ_, and a perforated plastic tube for the addition of water and nutrients and for aeration. Water and nutrient elements could be added at will to any section of the columns."

"Studies of the moisture tension changes in the several sections, as absorption by the plant roots dried the soil column from an initially low tension, were made with both boxes in which guayule was grown. For a period of several weeks (3 weeks in the case of box 2, 8 weeks for box 3) the moisture tension throughout the soil column was maintained at relatively low values (usually below 350 cm. of water) in order that the roots in all sections might be capable of normal absorption. Following this, all sections were irrigated to tensions of about 100 cm. of water.

Changes in moisture conditions in the several sections of the soil column were then measured by the instruments at frequent intervals (hourly, at first) as the plants lowered the moisture content to the wilting point range."

"In general, at a given time the tensions ranged from higher to successively lower values from top to bottom of the soil column. These data indicate that the roots extracted moisture held in the topsoil at fairly high tensions, while moisture was available at lower tensions in the subsoil. The same general behavior was noted with alfalfa. The greatest concentrations of roots were present in the upper part of the soil column, as is true under normal growing conditions. It is probable that this was an important factor.

"The following experiment was made to study the growth of guayule plants having water available to their roots in the subsurface layers of soil but with the surface soil at the permanent wilting percentage. After a period during which the whole soil column was kept at tensions of less than 1 atmosphere, no further irrigations were made, and during a period of about 3 weeks, moisture was removed by the plants from the six upper sections to such an extent that the Bouyoucos block resistances were in the range of 400,000 to 800,000 ohms. The plants were then defoliated, and during the next six weeks water was applied to only the five lower sections. With the top 32 inches of their root systems in soil having a moisture content of less than the permanent wilting percentage, the guayule plants put forth new leaves and continued to grow. Alfalfa behaved similarly, putting forth new shoots while the top 32 inches of soil was at or below the wilting percentage. Growth, however, was considerably less luxuriant than when moisture was available to the plants throughout the soil columns."

56. THE INTEGRATED SOIL MOISTURE STRESS UPON A ROOT SYSTEM IN A LARGE CONTAINER OF SALINE SOIL

C. H. Wadleigh. Soil Sci. 61: 225-238. 1946. The Williams and Wilkins Co. (Reprinted by permission.)

"The tension on the soil moisture at field capacity lies within the range of 0.1 — 0.4 atmosphere [Richards and Weaver, 1944]. Values for the soil moisture tension over the wilting range may vary widely, but the 15-atmosphere-percentage almost invariably falls within this range [Richards and Weaver, 1944]. Even though this

wide diversity in tension is found over the range of available moisture, it is frequently considered to be equally available throughout this range. The tenability of this postulate rests with the hyperbolic nature of the relationship between soil moisture percentage and tension [Veihmeyer and Edlefsen, 1937; Wadleigh and Ayers, 1945]. In other words, the soil moisture tension in most soils does not exceed 1 atmosphere until most of the available water is removed, but a tremendous increase in tension takes place with removal of the last portion of the available water.

"It is known that there are two groups of forces contributing to the decrease in the free energy of soil moisture: (a) the forces (hydrostatic, gravitational, adsorptive) which induce a tension upon the soil water; and (b) the osmotic forces due to dissolved solids in the soil solution [Bodman and Day, 1943; Day, 1942; Richards and Weaver, 1944]. As Richards and Weaver [1944] have pointed out, most discussions of the free energy of soil moisture have given inadequate treatment of the osmotic effects. They reported that soil moisture retention data derived from tensiometers or from pressure-plate [Richards and Fireman, 1943] or pressure-membrane [Richards, 1941] apparatus should be supplemented by a determination of the osmotic pressure of the soil solution in order to arrive at an evaluation of the energy relations of the soil moisture. Their studies indicated that the summation of the osmotic pressure of the soil solution plus the moisture tension at the permanent wilting percentage for many different soils covered a narrower range than did the corresponding values for moisture tension alone. Wadleigh and Ayers [1945] related this summation of the two groups of forces to the growth of beans in saline soil. For convenience they designated the aforementioned summation as the 'total soil moisture stress'.

"Thus, letting S designate the total stress in atmospheres,

$$S = T + \pi \quad (1)$$

where T designates the soil moisture tension in atmospheres, and π the osmotic pressure of the soil solution in atmospheres.

Obviously,

$$T = f(Pw) \quad (2)$$

$$\pi = f(Pw) \quad (3)$$

where Pw is the soil moisture percentage. It is evident, therefore, that as a plant removes water from a soil, the water stress upon the root system is continually increasing. Since this stress cannot be maintained constant, the rate of change of stress with time should be ascertained.

"The situation is further complicated in a saline soil by the fact that it is not possible for liquid water to move into and through a soil without carrying soluble salts with it. Consequently, if the container of soil is surface-irrigated, as is usually the case, solutes will tend to accumulate in the lower strata of soil. This means thatat constant soil moisture percentage throughout the soil mass there would be an increase in the osmotic pressure of the soil solution from the surface downward [Ayers, Wadleigh, and Magistad, 1943]. Under such a condition, even though the roots thoroughly permeate the soil mass there will be an unequal removal of soil moisture from different strata, the rate of removal being lowered as osmotic pressure of the soil solution increases. This is in accordance with observations from controlled experiments showing that rate of water absorption by plant roots is inversely related to the osmotic pressure of the substrate [Eaton, 1941; Hayward and Spurr, 1943, 1944; Long, 1943]. Such data enhance the validity of the main assumption made in the following presentation. That is, it is assumed that as water is removed from the soil mass, the total stress on the water being absorbed at a given time tends to approach uniformity in all the various strata of soil, even though the components of the total stress--osmotic pressure and tension--vary considerably among these strata."

"The primary assumption...was that the soil moisture stress over the various portions of the absorbing surface of the root system tends to approach uniformity. This assumption is fully in accordance with the second law of thermodynamics, in that it is assumed that the plant will not absorb water at a higher energy level if water is available at a lower energy level when the system is at equilibrium. But the tenability of this postulate is conditioned by the degree of constancy of the diffusion pressure deficit within the innumerable absorbing cells over the root system, and the degree to which equilibrium in this force is maintained among these cells. Furthermore, a growing plant is never in equilibrium with its environment. It is probable that the status of the two conditions pertaining to the absorbing forces of the roots deviates appreciably from the ideal. Variations in moisture stress over the root system may, to a slight degree, be concomitantly associated with variations in diffusion pressure deficit of the absorbing cells. Furthermore, this pressure deficit of the water in an absorbing cell is usually high enough that an appreciable variation in the pressure deficit of the external water is possible without exceeding that in the cell. Differences in magnitude of this diffusion pressure gradient would be reflected by variations in rate of absorption. In the final analysis, these variations in rate of absorption over the different parts of the roots system which were brought about by variations in the soil moisture stress would effectively tend to bring about uniformity in the external stress at a given time."

57. AN ESTIMATION OF THE VOLUME OF WATER MADE AVAILABLE BY ROOT EXTENSION

Paul J. Kramer and T. S. Coile. Plant Physiol. 15:743-747. 1940. (Reprinted by permission.)

"Modern views on plant-soil moisture relations stress the importance of continuous elongation of roots into new regions of the soil as an important factor in making water available to plants. It was long believed that as roots absorb the available water from the soil particles with which they are in direct contact more water is made available by capillary movement from more distant soil particles. Investigations conducted during the past 15 years indicate that this belief is not true, capillary movement of water toward the roots being so slow under average field conditions that it is of negligible importance. A brief discussion of soil-water relations will show why capillary movement is relatively unimportant.

"If a limited amount of water is applied to a large volume of soil a part of the soil will be wetted uniformly while the remainder is unaffected. This situation is often observed after a shower which has wetted the upper three or four inches of soil, leaving a sharp line of demarcation between the moist soil and the dry soil beneath. The movement of water in a dry soil can occur only from larger to smaller capillaries. As Puri (1939) has indicated, water will move from a wet soil to a dry soil only if the dry soil contains some capillaries smaller than the largest ones in the wet soil which are full of water. Water movement from wet soil to dry soil continues until contact is broken between the smaller capillaries of the dry soil which are responsible for the movement. When continuity of the liquid phase is thus broken visible movement of water ceases. The swelling of certain types of soil colloids when wetted is also of importance in inhibiting water movement by reducing the size of capillaries to a diameter so small that water molecules cannot readily pass. The amount of water held by capillarity in the soil after it had been uniformly distributed by gravitational and capillary forces is usually termed the field capacity (Veihmeyer and Hendrickson, 1931). Under field conditions well-drained soils are usually assumed to be at their field capacity a day or two after being wetted by rain or irrigation. Shantz (1927) stated that on theoretical grounds the capillary movement of water from moister to drier regions in soils at or below their field capacity would be very slow and this was experimentally verified by Keen (1927) and Veihmeyer and Hendrickson (1927). According to Puri (1939) when soil moisture is restricted to capillaries formed by particles having a diameter of 0.001 mm. or smaller relatively little water is available

to plants. He considers that particles coarser than clay are mainly responsible for retaining moisture available to plants, whereas clay aids in the conservation of this moisture by reducing its rate of movement. Livingston (1927), Keen (1927), Shull (1930), and others have pointed out that if little or no capillary water moves toward the roots then continual extension of the roots into new regions of the soil is essential to the absorption of an adequate supply of water."

"The volume of water made available daily by root growth was calculated for winter rye using the data published by Dittmer (1937). It was assumed that the roots contacted all soil particles in a cylinder 2 mm. in diameter and that 3.1 miles of roots were added daily. This amount of root extension would make available about 1.6 liters of water daily in a sandy loam soil at field capacity and about 2.9 liters in a heavy clay soil. It appears that at least under some conditions root extension might supply all the water required by a plant."

58. INFLUENCE OF DRY SOIL ON ROOT EXTENSION

A. H. Hendrickson and F. J. Veihmeyer. Plant Physiol. 6(3): 567-576. 1931.

Sunflower and beans were grown in moist soil contained in a waxed wire basket outside of which was soil at the wilting point. Results indicated that roots will not grow into soil which contains less moisture than the permanent wilting percentage.

59. ABSORPTION OF WATER THROUGH SUBERIZED ROOTS OF TREES

Paul J. Kramer. Plant Physiol. 21(1): 37-41. 1946. (Reprinted by permission.)

With a potometer Kramer measured absorption through the suberized portions of shortleaf pine and dogwood roots. In dry soil in June shortleaf pine took 3.37 cubic millimeters of water per square centimeter of root per hour during the day; at night absorption was 1.32 cubic millimeters. In wet soil in August absorption was 1.73 and 0.92. Dogwood roots were considerably more permeable than pine.

When soil is too cold or dry for root elongation, "...absorption through suberized roots may be of major importance. The number of small suberized roots in the soil under a forest stand is large enough to possess considerable surface and absorb an appreciable amount of water [Coile, 1937]. Since the soil is usually moist during the winter when root growth is slowest, conditions are such that most or all of the water required by evergreen trees probably can be absorbed through the mature, suberized roots. Even in the summer some water is doubtless absorbed through them, particularly when a rain follows a drought during which root elongation has ceased, and the roots have become suberized to their tips. Several days would be required following a rain for root growth to be resumed, but absorption through the older portions of the roots doubtless begins immediately."

60. MOVEMENT OF WATER VAPOR IN SOILS

Edward L. Breazeale, W. T. McGeorge, and J. F. Breazeale. Soil Sci. 71(3): 181-185. 1951. The Williams and Wilkins Co. (Reprinted by permission.)

Ninety percent saturated vapor was passed through a soil containing a growing tomato plant. Initially the soil was at field capacity. When soil dried and the plant wilted, soil samples were taken. For a soil with calculated wilting percentage of 7.55, moisture contents at wilting under vapor flow ranged from 2.85 to 2.93. For another soil with a wilting percentage of 11.27, comparable values were 5.32 to 5.50. When the experiment was repeated with dry air, the moisture content of soil samples at wilting point was very close to the wilting percentage.

"There was no definite sign of wilt for 30 days where air at a relative humidity of 90 per cent was passed through the soil, whereas for the dry air, wilt appeared in 17 days."

"The preceding experiments show that a highly vegetative plant, tomato, can survive for an extended period in soils at moisture contents well below the calculated wilting percentage with vapor as the only source of water."

61. PLANT ASSOCIATION AND SURVIVAL, AND THE BUILD-UP OF MOISTURE IN SEMI-ARID SOILS

J. F. Breazeale and F. J. Crider. Univ. Ariz. Agr. Expt. Sta. Tech. Bul. 53. 1934. (Reprinted by permission.)

"The pull or suction force of a plant for water amounts to about 7 or 8 atmospheres, that is, about 105 to 120 pounds per square inch, while the pull or adhesive force of the soil for water varies from zero in a saturated soil up to 25, 000 or more atmospheres in a nearly dry soil. In an ordinary air-dry soil the pull is approximately 1, 000 atmospheres. Therefore, when a plant is placed in a saturated soil, where the soil pull is practically zero, the balance of power is in favor of the plant, so water will move freely from the soil to the plant. As the percentage of water in the soil is reduced, the thickness of the moisture film is decreased and the pull of the soil for water increases. The pull of the plant for water remains fairly constant so at the wilting percentage the pull of the plant and the pull of the soil are balanced exactly; that is, each pulls about 8 atmospheres, and no water can be taken from the soil. If further loss of water from the soil takes place by direct evaporation from its surface, the pull of the soil will be increased rapidly. Under such conditions the water will move from the plant to the soil. The plant must either supply this water from that already stored up in its tissues, as in the case of the cactus, or it must absorb water from some other part of the soil which is above the wilting point, transport this water and exude it into the drier portions, or the plant will eventually wilt and die.

"It has been shown that a plant which has a tap root growing down into a moist subsoil, with its lateral roots in a surface soil which has been reduced to the wilting point, is able to draw a certain amount of water from the subsoil and to exude this water into the surface soil and keep the soil which is in direct contact with the feeding roots at near the wilting percentage. This phenomenon may enable a plant to tide over long periods of water stress."

"Most of the work which has been done hitherto upon the water requirements and wilting coefficients of plants in pot cultures indicates that a plant root cannot elongate into a soil which is below the wilting percentage. Under the conditions of these experiments this is unquestionably true, but in nature a plant does not always grow under the conditions which are imposed upon it in pot cultures. In humid regions parts of the roots of a plant are always in a subsoil where there is available moisture, while the surface roots may be in a soil which during a drought

is below the wilting percentage. It is the observation of the authors that, under such conditions, a root can elongate into a soil at the wilting percentage and even absorb a limited amount of plant food from such a soil.

"In the case of the mesquite or palo verde that grow in semi-arid regions, such as the Southwest, the conditions are often reversed. The tap roots may be in a relatively dry soil while the roots near the surface may be growing in a soil which is wet by occasional rains to a depth of only a few inches. It is evident from experiments that water is taken up by these surface roots, transported to lower levels, and exuded into the dry soil around the growing tips. In this way roots may grow into a soil mass which is below the wilting percentage, yet the growing tip, owing to a constant exudation of moisture, may never come into film-contact with a soil below the wilting percentage."

62. STUDIES IN TRANSPIRATION OF CONIFEROUS TREE SEEDLINGS

G. A. Pearson. Ecology 5(4): 340-347. 1924.
(Reprinted by permission.)

Western yellow pine, Douglas-fir, bristlecone pine, and Engelmann spruce seedlings were planted in pots containing a stony clay loam. During the growing season the pots were kept out-of-doors. Weighings were usually made every 3 or 4 days.

"...Observations were made in regard to the reaction of seedlings toward drastic reduction of soil moisture. On August 10, 1920, watering was discontinued in a series of pots which prior to that time had been maintained at a constant moisture content of 20 per cent, or approximately 9.5 per cent above wilting coefficient for the soil in question....The rate of transpiration began to fall immediately, and at the end of a month it was in most cases less than 3 per cent of normal. In the meantime the soil moisture had fallen to points varying from two to five tenths of one per cent above the wilting coefficient. During the next two months, transpiration was almost imperceptible.... Two yellow pine pots were watered on November 13, restoring the moisture content to 20 per cent. Immediately the transpiration rate shot up to the level maintained before the water supply was cut off...."

"The capacity of plants for extracting water from the soil depends upon their osmotic power and upon the ability to extend their roots in search of moisture. In the seedling stage rapid penetration

into the deeper soil layers is often a necessary condition for survival. Tests of the wilting coefficient indicate no large or consistent differences between the species with respect to pulling power upon the water of the soil. More exhaustive tests may show consistent differences, but it is almost certain that they would not be sufficiently large to give any species an appreciable margin over the others."

"When we turn our attention to rooting habits, we need not look far for outstanding characteristics which distinguish one species from another. When confined to a limited soil mass, as in the case of potted seedlings, the compact, fibrous root systems of spruce and fir place these species at an advantage. Western yellow pine is able to adapt itself well to such conditions, but not so the bristlecone pine. In their natural habitat the pines are particularly aggressive as to rooting habits. Within three months after germination, the taproot of western yellow pine is down from 15 to 25 centimeters. In the same period a spruce seedling will have penetrated scarcely one-third of this depth. Douglas fir is intermediate between the pines and spruces. Lateral extension depends much upon the proximity of other trees or of other deep-rooted plants. The firs and spruces usually grow in dense stands and have shallow, compact root systems. The pines grow in more open stands and have deeper and more extensive root systems. Of all the factors which figure in survival on a dry site, depth of root penetration during the seedling stage is undoubtedly the most important. Rate of transpiration is equally important; but, as far as the results of this study may be regarded as an indication, the difference between various species is not sufficient to constitute a deciding factor in drought resistance."

63. WILTING AND SOIL MOISTURE DEPLETION BY TREE SEEDLINGS AND GRASS

R. D. Lane and A. L. McComb. Jour. Forestry 46(5): 344-349. 1948. (Reprinted by permission.)

Black locust, green ash, brome grass, and tomato seedlings were grown in pots of loam and sandy loam in a greenhouse. Beginning at field capacity, daily water losses were determined by weighing and drying until the plants wilted permanently.

Pots containing brome grass had lower daily soil-moisture contents on both soils than other plants.

"A comparison of the total weights of water absorbed with dry weights of roots shows that tomato with the smallest root weight absorbed the least water, while brome grass with largest root weight absorbed the most water. The trees were intermediate with respect to both root weight and water absorbed. These data indicate that the weights of water absorbed were related to the dry weights of roots produced by the plants.

"Comparing grass with trees, leaf area, and soil water loss appear to be negatively correlated. Locust developed the largest leaf area and brome grass the smallest. Ash was intermediate. The position of brome grass in this list is the reverse of its position in the list based upon root weight; that is, brome grass had the smallest leaf area but absorbed the most water."

"Brome grass reduced soil moisture to the lowest level, the two tree species reduced it to an intermediate level, and tomato left the largest percent of soil moisture. Over-all statistical analysis of these data showed that the differences among soil moisture percentages at permanent wilting were highly significant. Individual comparisons of the wilting percents for different plants in sandy loam showed that only with tomato was the difference significant. On loam, however, there was a significant difference between the wilting percents of any two of the indicator plants. Differences among the wilting percents were greater on loam than on sandy loam soil."

	Mean soil-moisture percentage at permanent wilting	
	Sandy loam	Loam
Tomato	7.3	10.2
Ash	5.3	7.7
Locust	5.1	6.9
Grass	4.7	5.9

"The dry weight of roots may provide a rough measure of root ramification and of moisture-absorbing area in young plants. The authors think that the differences in the wilting percents obtained with the several indicator plants are due mainly to differences in the extent of root ramification."

64. A WATER COST OF RUNOFF CONTROL

A. R. Croft. Jour. Soil and Water Conserv. 5(1): 13-15. 1950.

Croft measured soil moisture on aspen, herbaceous, and bare plots. Evapo-transpiration deficits at the end of the growing season were 11, 8, and 3 inches respectively. "The reason water is saved by the removal of aspen is found in the distribution of its roots with respect to roots of herbaceous plants. The tree roots penetrate the soil to a depth of six feet or more. This is two to three feet deeper than herbaceous roots extend. Thus, three or four inches more water is available to aspen roots than to herbaceous roots. This additional available water probably accounts for the fact that the trees grow vigorously for about a month longer in the fall than herbaceous vegetation. The latter begins drying as early as August 1, presumably because it has used all the moisture available to its roots."

Croft doubts that thinning would increase water supplies, for "...additional water made available to fewer plants would merely result in lengthening their growing season. Eventually, however, the soil would dry out as much as with the unthinned stand."

"Water saving by altering plant cover probably can be achieved only when deep-rooted species are removed, or are replaced by more shallow-rooted plants."

65. AN OBJECTIVE LOOK AT THE VEGETATION-STREAM FLOW RELATIONSHIP

Richard S. Sartz. Jour. Forestry 49(12): 871-875. 1951. (Reprinted by permission.)

"With an unlimited supply of water available, some plants must certainly have the inherent ability to transpire more water than others. Except for stream-bordering and swamp vegetation, however, this variation is not important because transpiration rates are usually limited by the soil moisture available soon after precipitation has stopped."

"The amount of water that is lost through transpiration depends on two factors associated with the soil. One of these is the depth of the soil mantle. The storage opportunity of any soil profile is primarily

limited by its depth. The depth that plant roots penetrate may also be limited by the soil depth. Deeper root penetration means that more water is used because the root system has access to a larger reservoir. This has an indirect effect on stream flow: during the period when soil moisture deficits are being replenished, more of the precipitation is utilized in satisfying these deficits, and less contributes to stream flow.

"The other factor is whether or not the plant roots extend into the water table. Where this condition exists, the transpiration draft during the growing season can greatly influence the volume of flow. The amount, of course, depends on what proportion of the watershed is affected."

66. WATER AND TIMBER MANAGEMENT

Marvin D. Hoover. Jour. Soil and Water Conserv. 7(2): 75-78. 1952.

"It is necessary to distinguish between evaporation and transpiration because evaporation removes moisture mainly from the surface soil, while transpiration withdraws water uniformly from the entire root zone of plants. Differences in rooting habits of plants are important in determining the water used in transpiration. On the Piedmont of South Carolina, for instance, pine trees take water to a depth of six feet, while broom sedge, with more shallow roots, draws only to a depth of three feet. The more water available to tree roots, the more they will transpire."

67. THE DEPENDENCE OF TRANSPIRATION ON WEATHER AND SOIL CONDITIONS

H. L. Penman. Jour. Soil Sci. 1:74-89. 1949.

Penman reviews equations for predicting evaporation from open water surfaces, and previous determinations of the ratios of transpiration from turf to evaporation from open water. He points out that "The ratios are for conditions in which the grass always has plenty of water available.... In many years, however, particularly in southern England, natural turf suffers from lack of water, transpiration and growth-rates are reduced, and the problem of estimating the net deficit of water built up in the soil, while

remaining fundamentally meteorological, has biological and soils aspects added to it."

"Although many factors may alter it, one can ascribe to herbage a more or less definite root range in the soil, of the order of a foot or so. In this depth of soil there will be, at field capacity, a certain amount of water readily available for the plant upon which it can draw as easily as the turf referred to in the experiments outlined in paragraph 1. As an order of magnitude, the available water might be equivalent to 3 in. of rain, i.e., under the stated conditions the grass would be able to transpire 3 in. of water without needing to draw on supplies below the root zone, and without water-supply limiting the rate of transpiration. This, in effect, is an acceptance of the Veihmeyer [1942] concept of available water postulating a very narrow range of moisture content, or more correctly soil suction, on one side of which water is readily available, and on the other side of which the water is not available. The depth of the root zone, and the available water in it, might depend upon the composition of the herbage, its manurial treatment, the nature of the soil, the nature of the crop management, and the rainfall in the early part of the growing season. For the last two, for instance, one would expect frequent cutting to reduce the root range, and would expect a dry spring to increase it. Specification of the 'root reservoir' of water will be almost entirely guess-work, but the guess should not be inconsistent with the natural or imposed condition of the soil and crop.

"The plant roots may be regarded as exerting a drying potential. While they are using up the available water around them there will, of course, be some water movement upward from below, but it is convenient to make the slightly artificial assumption that the roots first use up the neighbouring water before the movement from below attains any appreciable magnitude. The drying after the exhaustion of the root reservoir should be the same as if the drying potential were applied to bare soil initially at field capacity, and its progress will then be represented by the drying curve obtained in laboratory experiments [Penman, 1941] which compared the evaporation-rate from bare soil with that from open water exposed to the same conditions. As this curve was the same for a sandy soil (Woburn) and a clay (Rothamsted), it will be assumed that it can be safely used for a range of soils."

The author constructs a drying curve with potential transpiration in inches of water as the abscissa, actual as the ordinate; at the origin (point 0) the soil is at field capacity. The root reservoir constant (in this case 3 inches of available water in the upper foot of soil) is plotted as

point A. From point A a line of unit slope is drawn to the origin. "From A, in the opposite direction we draw the moisture-depletion curve for bare soil. The curve has a slope of unity up to nearly 1 in. and then bends sharply to become, for practical purposes, a straight line of slope of about 1 in 12. When the soil moisture is represented by point 0, i. e., at the origin, the soil is at field capacity. As the integrated drying potential increases, the actual drying remains equal to it up to point A (i.e., the root reservoir has been transpired) and slightly beyond it; when it exceeds the root reservoir by more than about 1 in. the actual transpiration-rate decreases rapidly, i.e., the soil-moisture deficit increases very slowly."

The curve was used to keep a running record of soil-moisture deficit by months and to estimate the month when soil-moisture drainage would begin.

"In the first trials a root constant of 3 in. was used in all years and was reasonably successful, but it was noted that an improvement could be effected by increasing the root constant in years with a dry spring, and decreasing it in years with a wet spring. Qualitatively, this is acceptable: indeed, one might impose it a priori as a necessary condition to be satisfied, but quantitatively there is no justification other than expediency for the form adopted:

$$C = 5.0 - 0.6\Sigma R$$

where C is the root constant in inches and Σ R is the sum of the April and May rainfalls."

ROOTS

68. ROOT PENETRATION IN RELATION TO SOIL AERATION

R. E. Stephenson. Proc. 27th Ann. Report of 50th Ann. Meeting Oregon State Hort. Soc. pp. 19-34. 1935. (Reprinted by permission.)

"Good orchard soils (examined by Schuster and Stephenson) contain air spaces which vary in size from those that are barely visible to the eye (20 microns are just visible) (a micron is 0.001 millimeter) to those as large as a lead pencil. A few spaces, such as old root channels or animal burrows, are larger than this. Russian investigators found that the oxygen content of the soil air did not approach that of the outside atmosphere until the soil particles were 500 microns diameter, and the pore spaces correspondingly large. Air in smaller pores contained about one-fourth as much oxygen as the outside air."

"Examination of some thirty soils revealed few or no visible air spaces where tree growth was unsatisfactory. Further examination revealed that few or no roots enter those horizons of any soil lacking air space. Schuster's studies on root penetration in orchard soils has shown a distinct correlation between lack of aeration and the absence of tree roots. Roots passing through unaerated horizons are conducting rather than feeding roots which absorb moisture."

"When plants wilt, only the very small pores are filled with water, and these because of their smallness cling to their water with such force that plant roots are unable to pull it away. The pull exerted by root cells trying to remove water from the soil over the wilting range is estimated at 4 to 25 atmospheres. This is equal to a force of 60 to 375 pounds on a square inch of surface, trying to pull away the water.

"These forces when converted to capillary diameters (calculations by M. R. Lewis) indicate pores from 0.11 to 0.60 microns diameter. Only particles or aggregates of particles of collodial size (1.0 to 2.0 microns down) afford such small pore spaces. A Sites clay with 50 per cent pore space, showed nearly 90 per cent of its pores full of water at the wilting point. Then 90 per cent of the pores are of an order of magnitude of 0.60 microns diameter or less. This is in the sixth foot, where the total clay is 62 per cent and the two micron clay is 40 per cent.

"The moisture content of soils corresponding to the moisture equivalent is about equal to the field capacity. Thomas gives 10 microns as the diameter of pores (assuming pore diameter equals the particle diameter) which are entirely filled with water at this moisture constant.

Ten micron pores correspond roughly to silt size particles. Smaller particles and their open spaces hold capillary water and, therefore, exclude the air. A 10 micron pore corresponds roughly to an attractive force equal to one fourth of an atmosphere, or less than four pounds on a square inch. Such water is readily removed by the roots of plants, provided the soil is aerated and penetrable.

"Soils high in clay and fine silt may be entirely water-logged. The Sites soil spoken of above contains more than 70 per cent of the clay and fine silt in the fifth and sixth feet. The pore spaces are all of an order of magnitude of 10 microns or less. The soil is entirely water-logged at field moisture capacity. This condition has been described as water-logging without a water table."

"We have tentatively placed soils with less than 5 or 6 per cent of air space (non-capillary pores) in addition to the space occupied by water (capillary pores) in the class of undesirable soils. Such soils may have high moisture capacity, but room for root development and penetration is too limited. Soils with 10 or 12 per cent or more of air space over and above space occupied by water at field capacity are desirable, and favorable to deep penetration and strong root development. Soils between these two groups are somewhat marginal."

"The following table gives an idea of how the size of soil particles affects the rate of movement of moisture in soils.

Size of Soil Grain	Penetration Rate of Water	Relative Rate of Water Penetration
1 micron (collodial clay)	1 inch in 41 days	1
10 microns (fine silt)	1 inch in 10 hrs.	100
100 microns (fine sand)	1 inch in 6 min. 1 ft. in 1-1/5 hrs.	10, 000
1000 microns (coarse sand)	1 inch in 3-3/5 sec. 1 ft. in 43 seconds	1, 000,000

"The data (calculations by M. R. Lewis) are based upon Schicter's formula assuming uniform size and spherical particles with most open packing. This formula was checked by King of Wisconsin on field soil. The rate above assumes a constant head (supply of free water), a downward movement, and a free outlet. Upward movement against gravity

would be normally many times slower. In addition to indicating the impossibility of upward movement of water through fine pores, the data serve to indicate how a few large pore spaces, between either soil grains or aggregates of grains, aid materially in drainage and aeration of soils.

"More than a month for one inch of water to move through an inch of tight clay! The trees might be dead in less time. These tight subsoils in the fourth, fifth, and sixth feet depths, have wilting points as high as 40 per cent, when plants are grown in the greenhouse with roots in contact with the soil. How impossible for the moisture to reach roots two or three feet above!

"By contrast, Weaver states that young, actively growing roots in a permeable soil may grow at rates of half an inch to two inches a day. The roots go after the water when they can get through the soil. They can get through only when there are open, aerated pore spaces.

"Tight soils offer mechanical resistance to root penetration. No data on the size of tree roots is available. Weaver reports that some vegetables and grasses have roots as small as one-tenth-millimeter (100 microns) diameter. The growing root tip with its root cap is probably larger than this. There are few or no open spaces between the soil particles in the Sites soil at the fifth and sixth feet depths larger than about 10 microns. Ninety per cent of the pores are less than this. A root 100 microns diameter must have a hard time penetrating an opening ten microns or less in diameter. (Try crawling into a gopher hole). Russell stresses the mechanical resistance which clays offer to root penetrations.

"Even root hairs, the smallest part of root systems, are 5 to 10 microns diameter, or larger than many of the open spaces in heavy clay soils. There are few roots, and few or no root hairs on the roots, in tight subsoils. The tree or other plant is unable to provide an absorbing system (the small young roots and the root hairs are the absorbing system) in heavy unaerated soil.

"The few roots that are found in heavy soils appear to have found entrance through worm holes, insect burrows, cracks, and old root channels. We have found mats of absorbing roots on the cleavage surfaces of cracks in the rock six and eight feet down. After the root finds a hole through a heavy horizon, and comes into open space or more permeable layer, profuse branching may occur. Most of the roots in heavy soils, however, are confined to the shallow depth of the

surface, that is more permeable and better aerated. Often the first and second feet are noticeably full of holes, cracks, and cavities made by various means. These permit root development."

"Shallow soils are a handicap. Soil is only as deep as roots can penetrate and obtain air and moisture. Soils may be 20 feet to rock but if roots utilize only three feet that is the practical, or usable soil depth."

69. SOIL FACTORS IN RELATION TO ROOT GROWTH

W. Stephen Rogers. Trans. 3rd Inter. Cong. Soil Sci. 1:249-253. 1935.

A study of the root systems of apple trees 10 to 11 years old showed that: "In all cases the roots spread farther than the branches. In the sand, the root spread was two to three times the branch spread. In the loam and clay about 1.6 times the branch spread...The stem-root ratio [by weight] varied in the different soils. On loam it was about 2.2, on clay 2.1, and on sand about 0.9. Hence it required more than twice as much root to support a given amount of top on the poor soil as on the loam or clay [Rogers and Vyvyan, 1934]."

"The type of root is largely modified by the soil. In the poor sand, the roots are very long, thin and straight. In the clay, the roots were shorter and stouter, tapering and rapidly branching, and twisting in all directions. In the loam they were intermediate in character. In spite of this modifying influence of the soil, the roots of the different rootstocks retained their own distinctive characters."

"...In irrigated orchard...the soil dried almost equally at 1 foot and 3 feet since the roots of the trees and cover crop extended throughout the soil to this depth."

"...As the soil temperature rose, the root growth, as shown in both number and length of roots, increased also. A fall in temperature was followed by a fall in root growth. When the soil became drier, root growth decreased although the temperature was rising. When irrigation was applied, the root growth rose again sharply....It appears that root growth has varied directly with soil temperature, with sufficient moisture as a limiting factor."

"The new roots are white, with numerous tiny root hairs. After a period of two to four weeks these hairs shrivel up, and the cortex be-

comes suberized--finally sloughing off through action of soil insects and organisms. The root is thus left loose in its hole until secondary thickening begins. Many of the finer roots rot away entirely, leaving numerous channels which must be of great value in aerating and draining the soil. Meanwhile new root growth continues to comb the soil through and through."

70. THE GROWTH OF FOREST TREE ROOTS

W. B. McDougall. Amer. Jour. Bot. 3(7): 384-392. 1916.

At the University of Illinois the author observed root growth of silver maple, basswood, hickory, and white oak through a square foot of glass set horizontally over roots beneath humus, and through a similar square at the end of a trench two feet deep. The glass was covered with felt to keep out light. Readings at midday in summer injured or killed roots by exposure to air; observations made at sunrise with two years of record showed that growth started in early spring and continued as long as soil was wet until November or December.

McDougall believed that periodicity of growth is not due to internal causes. "The results recorded in the present paper show conclusively that the resting period of the roots studied are not fixed and hereditary since, in 1914, although most of the roots under observation had a summer rest, some of the hickory roots did not have; and in 1915 there was no summer rest period in any of the roots studied, unless it occurred after September 1, which would be most unlikely... In 1914 there was very little rainfall from early spring until the end of August. The soil thus became progressively drier and reached a minimum of water content toward the end of August. The rate of root-growth also gradually decreased and ceased entirely in most cases sometime in July, to begin again only after the heavy rains of August 28. In other words, the summer period of rest was only during the period of drought. In 1915 there was no period of drought and, naturally, no rest period. The hickory roots which did not have a rest period during the summer of 1914 were some of the most deeply located roots upon which observations were made, and, naturally, the soil was not so thoroughly dry at that depth as nearer the surface. It is probable that observations on still deeper roots would show all roots located where adequate moisture was available growing throughout the period of drought."

"It seems reasonable to conclude, then, that the summer rest period, when it occurs, is due not to any inherent tendency toward

periodicity but to a lowering of the water supply. As to the winter rest period, the results show a close relation to temperature. But temperature to a certain extent controls the water supply, since a lowering of the temperature renders absorption increasingly difficult and thus reduces the amount of physiological water. In this case, therefore, the rest period is due indirectly to temperature but more directly to a decrease in the available water supply."

71. SEASONAL GROWTH OF GRASS ROOTS

Irene H. Stuckey. Amer. Jour. Bot. 28: 486-491. 1941. (Reprinted by permission.)

Grasses were grown in well-drained loam soil at the Rhode Island Agricultural Experiment Station. "For some of the species the whole root system was regenerated annually, with active production of new root growth beginning in October, continuing slowly through the winter and increasing rapidly after the spring thaw in March with its maximum in April. After the middle of June, few, if any, new roots were formed and there was no appreciable growth of existing roots until October. Most of the old roots disintegrated shortly after the new ones developed. These species included timothy, timothy S-50, meadow fescue, rough-stalked meadow grass, perennial rye grass, probably colonial bent, and redtops."

"With other species the development of roots during the first year was essentially the same as that described above, but only a small percentage of the roots disintegrated, and after the first spring only a few new roots developed. Most of the new roots developed during the second year were at the nodes of new rhizomes. The species with 'perennial' roots are Kentucky bluegrass, Canada bluegrass, crested wheat grass, and orchard grass."

72. WINTER ROOT GROWTH OF PLANTS

F. J. Crider. Sci. 68: 403-404. 1928.

At Boyce Thompson Southwestern Arboretum, Superior, Arizona, Crider observed roots of plants growing in large boxes provided with plate-glass fronts.

He found that roots of certain plants generally thought to be dormant in winter make definite continuous growth at this season. This was true of both deciduous and evergreen species. Notable examples were Prunus persica, Prunus armeniaca, Covillea tridentata, Simmondsia californica, Cupressus arizonica, and Opuntia laevis. Rate of root elongation per day varied from 9 millimeters in November as the maximum to 0.5 millimeter in February as the minimum. Growth was evidently affected by change in seasonal temperature of the soil, but there was no direct or close correlation between daily growth and soil temperatures. Average daily root elongation of peach (P. persica) for the winter period November 4, 1927, to March 31, 1928, was 2.10 millimeters. Average daily growth for November was 5.55 millimeters, for December 2.01 millimeters, for January 1.65 millimeters, for February 0.90 millimeters, and for March 1.16 millimeters.

Other plants under the same environmental conditions made no root growth in winter: Citrus aurantium, Vitis vinifera, Prosopis velutina, Parkinsonia torreyana. The period of their root inactivity began about the first of December and lasted until the latter part of March.

73. DISTRIBUTION OF ROOTS OF CERTAIN TREE SPECIES IN TWO CONNECTICUT SOILS

G. I. Garin. Conn. Agr. Expt. Sta. Bul. 454. Jan. 1942. (Reprinted by permission.)

Garin studied the root distribution of white pine, red pine, Norway spruce, white ash, and red oak on loamy sand and fine sandy loam.

"Root development of a forest plantation can be pictured as passing through four stages. The first stage is that of free root growth, when roots have space in which to develop without coming near the territory occupied by those of other trees. The second is that of root invasion, when the expanding root systems begin to intermingle and invade areas adjacent to other trees. This stage is reached at a very early age in the forest plantation. The third period, that of root competition, begins when root capacity is reached. In some soils this may be much sooner than in others. On poor dry soils this period, in most cases, precedes the closing of the tree crowns above the ground. Observations show that, in poor soils, roots of trees of about the same height and the same age spread more widely and occupy a much larger volume of soil than those in richer soils. On rich soils the stage of root competition

may follow the closing of the crowns. The third period would prevail throughout the greater part of the life of the stand. A fourth stage, that of release from root competition, begins when mature trees start to die and release a sufficiently large area from root competition so the new reproduction can become established. Trees at this stage do not have the vigor to replace to the point of 'root capacity' the areas release by dead trees, before new reproduction becomes established."

74. DEVELOPMENT AND ACTIVITIES OF ROOTS OF CROP PLANTS

John E. Weaver, Frank C. Jean, and John W. Crist. Carnegie Inst. Wash. Pub. 316. 1922. (Reprinted by permission.)

"The importance of root extent and distribution in a study of soil-moisture is patent. These should determine not only what depth of sample should be used, but also the maximum depth to which samples should be obtained. The time, method, and amount of the application of water for irrigation studied in the light of root development furnish a rich and varied field for investigating problems of the greatest scientific and economic importance. Conversely, the proper drainage of swamps and boglands for pastures, meadows, afforestation, or for cultivated crops, should be determined with reference to root relations. (Cf. Howard, 1916, 1918; Osvald, 1919.)"

"It seems not improbable that some of our best yielding crops may be able to outstrip others largely because of their greater efficiency in securing a larger and more constant supply of water and nutrients. Why certain artificial mixtures of grasses and other herbs may thrive in pastures and meadows, while others do less well, must depend to a large degree upon competition of root systems. This is the case in native grassland, where it is usual for 200 to 300 individuals or groups of individual plants to grow in a single square meter, due to lessened competition resulting from absorption at different soil-levels and from maximum above-ground activities at different times of the growing-season."

"The investigations here recorded were carried out during the growing-seasons of 1919 to 1921. Stations were selected at Peru and Lincoln, Nebraska, at Phillipsburg, Kansas, and at Burlington, Colorado. These stations have a mean annual precipitation of about 33, 28, 23, and 17 inches respectively. The differences in climate are clearly expressed in the type of natural vegetation. The true prairies at Lincoln give way southeastward along the Missouri near Peru to the sub-

climax prairie, which is potentially chaparral or woodland, the grasses having possession only because of such disturbances as grazing, fire, mowing, etc. At Burlington, in eastern Colorado, a typical expression of the short-grass plains is found, while in north-central Kansas at Phillipsburg short-grasses intermingle with the taller ones and constitute mixed prairie (Clements, 1920; Weaver, 1920). Crops were grown at the several stations under measured environmental conditions for the purpose of determining not only the nature of the root system, but especially also its distribution and extent at various stages of growth. The work was conducted under field-crop conditions and methods of tillage in order that the results might faithfully portray the root relations of crops as grown under usual farm practice. Moreover, extensive experiments have been conducted both in the greenhouse and under field conditions to determine the active working-level of the roots of cereals and other crop plants as regards the absorption of water and nutrients at various stages in their growth."

At Peru, Nebraska, the surface 1 to 1.5 feet of soil was a dark-colored silt loam. This overlaid a deep mellow loam.

"All the cereals, including corn, possessed a root system in which there was a definite group of more or less horizontal, spreading roots lying within the first 1 to 1.3 feet of soil, and a second group of deeply penetrating roots extending into the subsoil to depths of 6 or 7 feet."

"The Early Ohio potato differed from the other plants in that the same group of roots which at the outset formed the shallow portion of the system subsequently became the deeper portion by turning more or less abruptly to the vertical position and growing downward."

"The more superficial roots reached their maximum development first. In most cases this occurred about the time the top had reached an intermediate stage of growth; the deeper roots developed coordinately with the top and thus balanced water absorption and transpiration."

"Oats reduced the soil moisture to a greater degree than any of the other small cereals. Corn in its later stages of growth was an extravagant user of water. The potato showed the greatest variation in the number and extent of its roots."

At Lincoln, Nebraska, the soil was a silt loam, much more compact than that at Peru. Crops were not so deeply rooted as those at Peru.

At Phillipsburg, soil was a silt loam of the Colby series. Root depth exceeded that at Lincoln. With high water loss in surface soil in June and July, crops developed root systems that went far into the deeper moist soils.

At Burlington the soil was a fine sandy loam with hardpan at 2 to 2.5 feet which was not penetrated by the roots.

"The differences found in the lesser height-growth, smaller yield, and less extensive underground parts, going from the more mesophytic eastern stations to those of greater aridity westward, correlate directly in nearly every way with the growth of native vegetation, whether trees, weeds, or species of the native grass land are considered. The native vegetation growing through a long period of years integrates the climatic conditions during its growth. Thus it is not only an expression of the present conditions, as is true largely of rapidly maturing crops, but is to a large extent a record of conditions that have obtained during a period of many years."

"This increasingly greater root depth as one goes eastward from the short-grass plains into regions where the deep subsoil is constantly moist is in agreement with determinations made on the root depth of cereals at 14 stations during 1919. Using root extent in the true prairie as unity, the relative depth in mixed-prairie and short-grass plains was as follows: Working depth of rye, 100: 92: 69; oats, 100: 95: 79; winter wheat, 100: 93: 61. Maximum depth of rye, 100: 90: 65; oats, 100: 94: 77; winter wheat 100: 80: 51.

"...In nearly all cases where the roots of crop plants were excavated, the total development below the cultivated soil-layer was as great and usually much greater than that in the surface soil. Among native plants, the bulk of the root system in the great majority of cases lies below the surface foot, and the same holds true for many crop plants, including especially the fall-planted cereals. The dependence of plants upon the deeper-seated portion of their root systems is well illustrated in times of drought, where the vegetation remains unwilted and crops do fairly well even after the water in the surface 6 inches of soil has been nearly or entirely exhausted."

75. THE SUBSOIL

Eric Winters and Roy W. Simonson. Advances in Agronomy 3:1-92. Academic Press, Inc. New York. 1951. (Reprinted by permission.)

"It is common to speak of deep-rooted and shallow-rooted plants, although the two are not distinct groups. Deep-rooted plants could more appropriately be designated as those which can develop deep root systems under favorable soil and moisture conditions. For example, alfalfa, sweet clover, and apple trees (*Malus* spp.), are generally considered to be deep-rooted plants. Working in Kansas, Grandfield and Metzger (1936) found that alfalfa removed moisture from permeable soils to depths of 25 ft., whereas Myers (1936) noted the roots of two-year-old sweet clover at depths of 13 ft. Sweet (1929) reported apple tree roots well below 10 ft. in certain soils of southern Missouri, and similar observations were made by Browning and Sudds (1942) in West Virginia. Generally speaking, deep penetration occurred in soils which were relatively open and permeable throughout the profile. By way of contrast, the authors have observed alfalfa and sweet clover roots which failed to penetrate claypans and fragipans at depths of 18 to 30 in. Roots extended down to the pans but not into them. Sweet (1929) reports that the roots of apple trees were confined to that part of the soil above the hardpan or claypan. Browning and Sudds (1942) noted that the root systems were shallow in soil types with heavy subsoils. Thus, plants which are ordinarily deep-rooted may be restricted in root penetration by the character of the subsoil."

"Although shallow-rooted plants usually have the major part of the root system in the upper soil horizons, this varies with the character of the soil profile. For example, corn roots are almost completely restricted to the A horizon by the claypan in Putnam silt loam in northern Missouri, whereas they extend to depths of 5 or 6 ft. in the friable Marshall and Monona soils of western Iowa. This variation illustrates the flexible rooting habits of some plants. Because of that flexibility, the adaptations of shallow-rooted plants to soils is influenced less by root penetration relationships of subsoil layers than is the adaptation of deep-rooted plants."

"The differences in the ability of the roots of plants to penetrate certain kinds of B horizons is worth noting. Taking corn and alfalfa as examples, the root systems commonly extend into and through the B horizons of zonal soils. It is true, however, that alfalfa and other perennial plants are better able than corn to penetrate B horizons that are high in clay, provided the soils are well drained and well aerated. This difference in root penetration is probably related to the length of

the growing season and the length of life of the plants rather than to differences in rate of penetration. Corn grows during a relatively short season and its period of root elongation is limited, probably being completed by tasseling time. Alfalfa grows from early spring to late fall, a much longer period. Furthermore, alfalfa root penetration can continue beyond the one season as the plants grow in subsequent years."

". . . Simple mechanical difficulties in root growth can be expected as a general rule in claypans. Coupled with restricted aeration, these mechanical difficulties provide adequate reason for the limited penetration by most plant roots."

"The difficulties of root penetration in fragipans and hardpans are due to one or more of the following: high bulk density or volume weight, low pore space, restricted aeration, or low fertility status."

"Deep rooting can seldom be expected in soils with well-developed fragipan or hardpan layers as parts of their profiles. Field observations indicate that roots seldom penetrate such layers. Consequently, it does not seem probable that subsoils consisting of fragipan or hardpan layers can be improved by the growing of deep-rooted plants. It may be possible in exceptional instances. Chevalier (1949) reports that a laterite crust disappeared in forty years under a good stand of forest. Comparable experiences with fragipans and most hardpan layers, however, seems to be lacking."

"The gradual deterioration of structure in soils such as Paulding clay under cultivation suggests that trees were able to improve physical properties of soils, especially in the deeper horizons (Bradfield, 1936). Lutz and Griswold (1939) state that tree roots may influence soil morphology by pushing soil material aside as they grow, by leaving channels when they decay, and by the mixing of soil materials when trees are blown over by the wind. Their studies of Podzols and Brown Podzolic soils in profile pits in New Hampshire indicated significant disturbance and mixing of horizons by windthrow of individual trees in ordinary forest stands. Page and Willard (1946) suggest that the gradual decay and disappearance of coarse tree roots originally present in soils under forest may be reflected in gradual deterioration of physical properties of soils under cultivation. Yeager (1935) found that trees growing in Chernozem and Humic-Gley soils of eastern North Dakota had about 97 per cent of their roots, on the average, in the uppermost 4 feet. Inasmuch as trees are not the indigenous vegetation on Chernozems, growing conditions are less favorable for them than they are on podzolic

soils in more humid regions. Even so, some tree roots penetrated to depths of 10 feet and many to depths of 4 feet. More direct information on the influences of tree roots on soil properties may be taken from experience with shifting cultivation in the Belgian Congo (Kellogg and Davol, 1949). Rotation systems are followed in which crops are planted in corridors or strips that alternate with the native forest. Optimum rotations provide for cultivation of a corridor from four to eight years, after which it is kept in forest about as long. This practice is essential to the maintenance of satisfactory physical properties of the soils. Chevalier (1949) also emphasizes the importance of 'bush fallow' in maintaining soils in good physical condition in French Guinea. Problems of structure maintenance in the cultivation of Latosols seem to differ greatly from those common to podzolic soils. For the most part, granulation is encouraged and sought for in podzolic soils, whereas it must be controlled and sometimes prevented in Latosols. These various observations indicate that tree roots may serve in several ways in the improvement of subsoil conditions or in the maintenance of satisfactory conditions for plant growth. As with data on the effects of other types of roots, however, precise information as to the kinds and magnitude of effects are still lacking."

76. EFFECTS OF DIFFERENT INTENSITIES OF GRAZING ON DEPTH AND QUANTITY OF ROOTS OF GRASSES

J. E. Weaver. Jour. Range Managt. 3 (2): 100-113. 1950.

Quantity of roots was determined in three pasture types near Lincoln, Nebraska, by washing roots free from soil monoliths. Monoliths of Carrington silt loam were taken in a high-grade pasture mostly in little bluestem but with about 15 percent big bluestem, in a mid-grade pasture with about half bluegrass and little bluestem that had been weakened by grazing, and in a low-grade pasture mainly in bluegrass and blue grama.

"[There were] ... remarkable changes in root depths in the three grades of pasture. As the native mid and tall grasses weakened and died and were replaced by low-growing bluegrass and blue grama, both depth of soil occupied by roots and the amount of root material decreased greatly. Oven-dry weights of roots and percentage decrease at each soil level are shown in Table 1.

Table 1

Dry weight in grams of underground plant material at the several soil depths in three grades of pasture and percentage decrease from the high-grade type

Depth	High-grade	Mid-grade	Decrease	Low-grade	Decrease
ft.	gm.	gm.	%	gm.	%
0 -0.5	65.50	52.20	20	28.14	57
.5 - 1	9.10	8.55	6	4.13	55
1 - 2	6.93	6.52	6	2.66	62
2 - 3	2.39	.95	60	.14	94
3 - 4	.40	.17	58	- - -	100
Total	84.32	68.39	19	35.07	58

"The chief cause of the greater weight of materials in the surface 0-0.5 foot compared with that of the second layer is the great abundance of stem-bases and rootstocks near the soil surface. These often equal the weight of the roots. They, of course, are lighter in worn-down bluestems, and especially in bluegrass and blue grama. But the roots at all depths decreased greatly and especially those in the third and fourth foot....Loss of roots in the deeper soil or death of all the roots in this part results in a much restricted volume of soil from which water and nutrients may be absorbed."

"The degeneration of the bluestem grasses under different intensities of grazing was further examined. This was done by the study of representative individual bunches. One bunch of little bluestem was selected from a portion of the pasture where grazing for several years had been very light or none. The last year's stubble was thick, continuous, and 8 inches tall. The bluestem was in a very vigorous condition. A second bunch was selected in the mid-grade area. Apparently it had been grazed closely for at least two years. There was only a little debris left from preceding years. The individual tufts composing the bunch were abundant but more or less separated by bare spaces; hence the crown was somewhat open. The third clump was from a portion of a low-grade area where little bluestem still persisted but in a much weakened condition. The bunch was very open, much bare soil was exposed because of this and the lack of a good mulch. The individual tufts of grass were short and much stunted. Many fragments of dead tufts were present. A monolith of soil 12 inches wide and 4 feet in depth was taken directly below each bunch."

"Decrease in the density of the rootmass at all levels from the high-grade to the low-grade pasture is clearly evident. The roots were almost 5 feet deep in the first sample, about 4 feet in the second, but they extended to only about 3 feet in the third."

"The high weight of the first sample in the shallow soil is characteristic of this species and is due in a large measure to the weight of underground stem-bases and short rootstocks. Decrease in weight at all depths in the second sample is very great. The weight, compared with that of the first sample, decreases regularly with depth from 19 to 91 percent (Table 2). Total weight of the second sample was 55 percent less than the first. In the second sample the roots were not only fewer than in the first but also finer. Their diameter was only a half to a third as great. Some dead roots were found. In the third sample differences were even more marked. Branches were fewer, many roots were dead, and debris from decaying roots was abundant. There were no roots in the fourth foot. . . . It seems clear that root deterioration is from the tips upward toward the crown. This sequence has been noted several times and the actual process was observed in Sudan grass as a result of frequent clipping [Peralta 1935]."

Table 2

Dry weight of underground plant materials of little bluestem at the several depths in the three grades of pasture and percentage decrease from the high-grade type

Depth	High-grade	Mid-grade	Decrease	Low-grade	Decrease
ft.	gm.	gm.	%	gm.	%
0 - 0.5	44.60	18.99	57	10.17	77
.5 - 1	2.74	2.21	19	1.63	40
1 - 2	2.59	1.61	38	1.07	59
2 - 3	1.20	.64	47	.21	83
3 - 4	.75	.07	91	---	--
Total	51.88	23.52	55	13.08	75

"Similar studies were made on root deterioration of big bluestem, except that bluegrass invaded the area occupied by this species in the low-grade pasture. The process of deterioration of the root system was about the same as that of little bluestem.

"Here the loss in root materials below the first foot again increased with depth. Weight of the root system in mid-grade pasture was only half that in high-grade, and in low-grade pasture it was only one-fourth as great."

"Just as the forage yield may be increased by good pasture management, so too the root systems of the grasses will be improved somewhat in proportion. A good top that produces much nutritious forage and a good root system that can withstand drought and store much food for early growth in spring go hand in hand. A depleted range of non-vigorous grasses is usually also one in which the root systems are absorbing water and nutrients only in the upper portion of the soil."